

高エネルギー宇宙の総合的理解:

直接観測に基づいた
衝撃波粒子加速研究の現状

寺沢敏夫(東大理)

内容

Introduction

衝撃波加速の観測例(地球周辺、SN1006、...)

CME衝撃波と電子の加速、II型電波バースト、ドリフト加速

(註) III型電波バースト、リコネクションに伴う加速

標準理論(衝撃波統計加速)とその観測的基礎

CME衝撃波の例、波動励起メカニズム

標準理論の拡張1... 磁場の増幅? Lucek and Bell機構

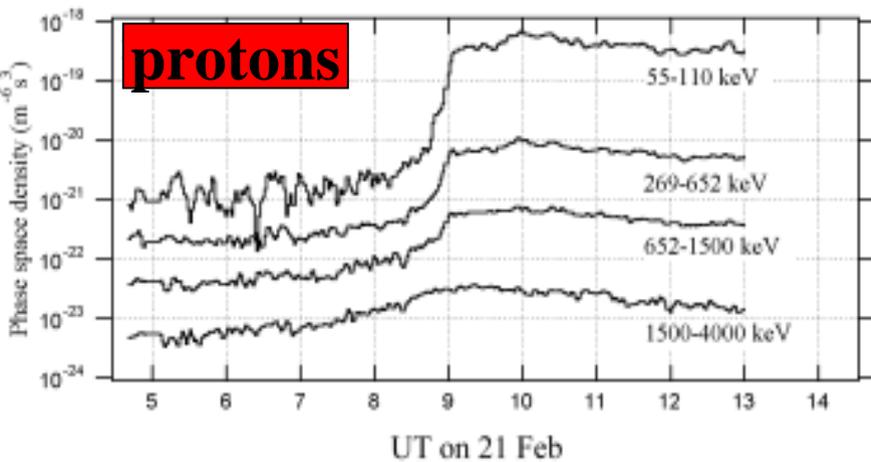
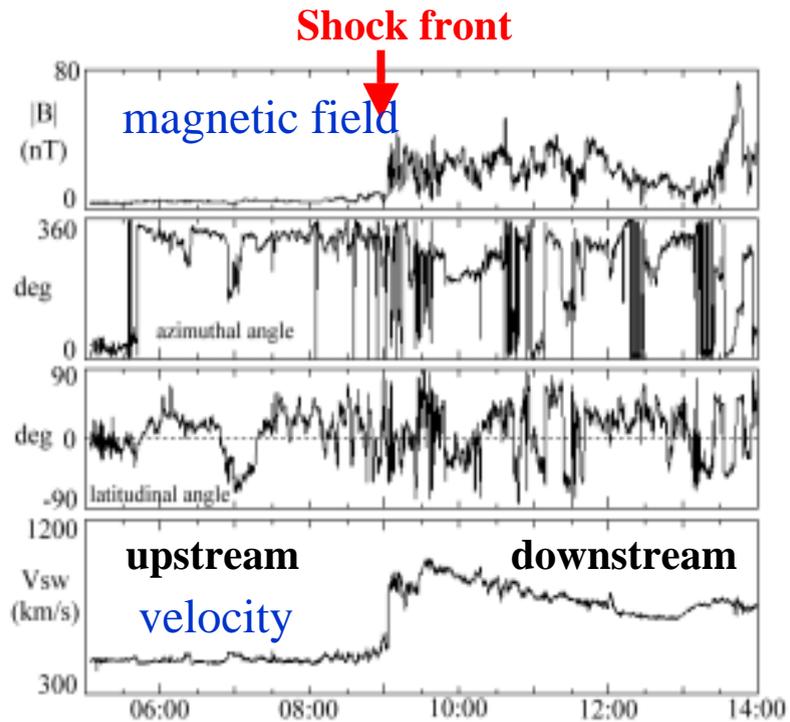
標準理論の拡張2... 加速の反作用 Cosmic Ray Mediated Shocks

More about SEP (solar energetic particles)

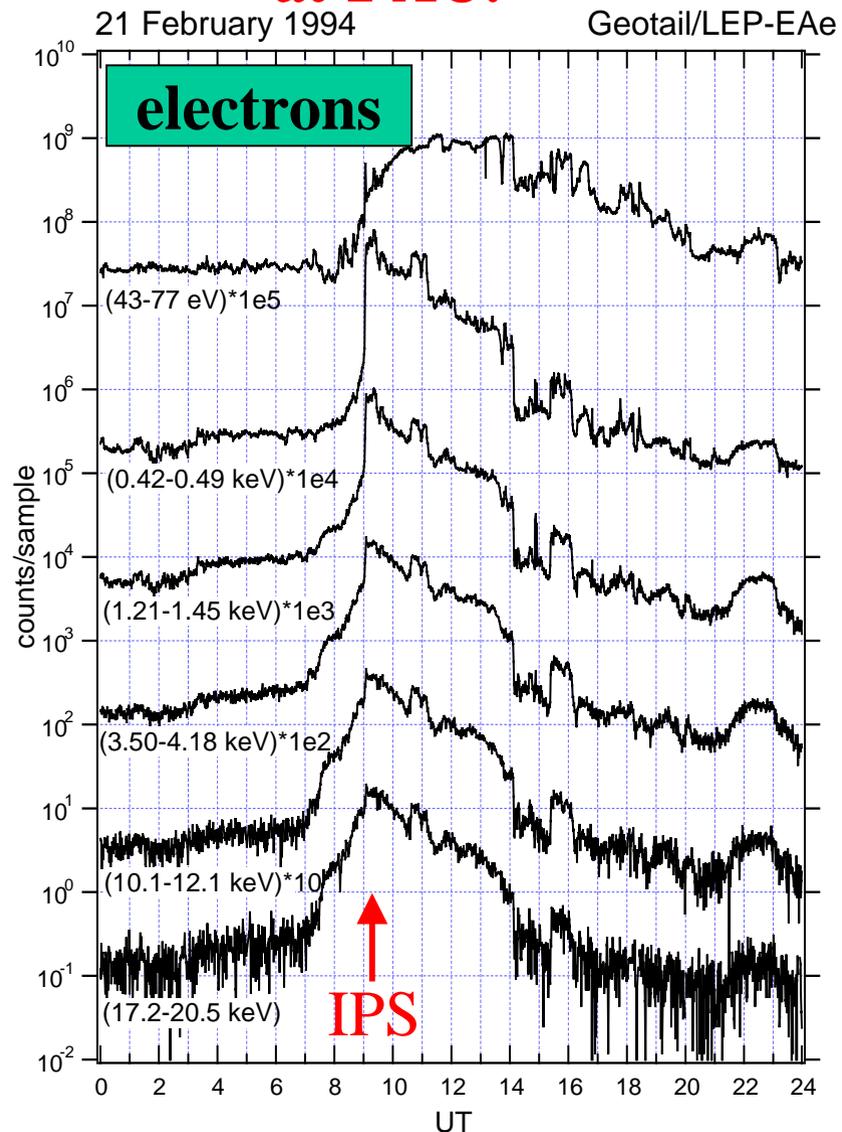
Ions vs. electrons

A CME shock on 1994/2/21

(Shimada et al. Ap. Space Sci., 1999)



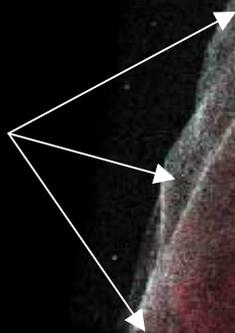
Evidence of diffusive acceleration both for ions and electrons at 1 AU.



SN1006

NE-Rim

Shock Fronts



shock heated plasma in
narrow layers

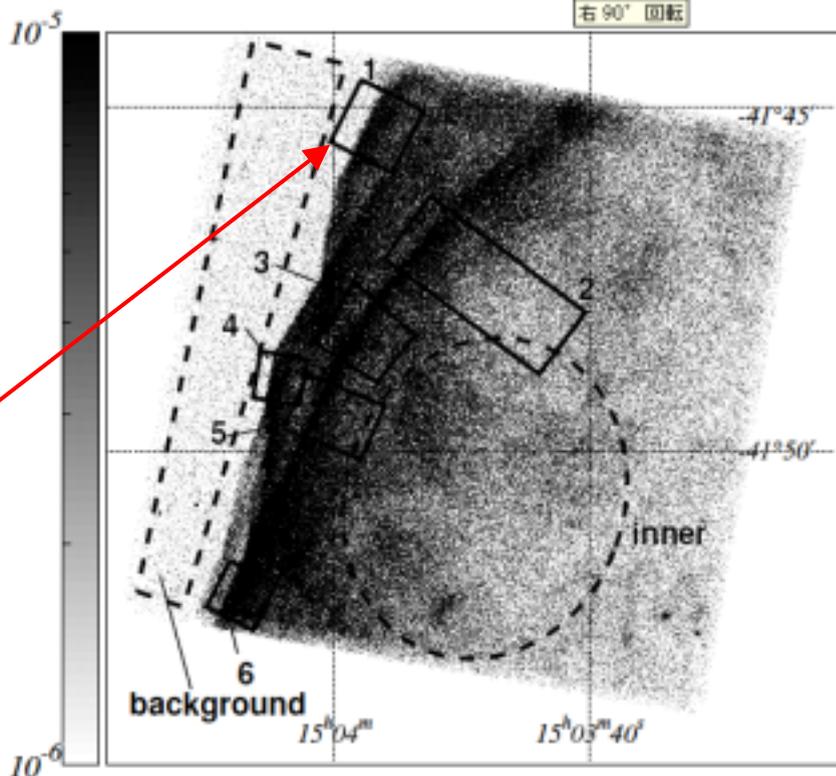
$0.01 \text{ pc} \sim 10^{16} \text{ cm} \sim$
electron gyro-radius
of 10 TeV

Fermi acceleration model
→ large diffusion is required
diffusion coefficient
 $\eta = D/D_B \sim 1$ (Bohm limit)

Chandra

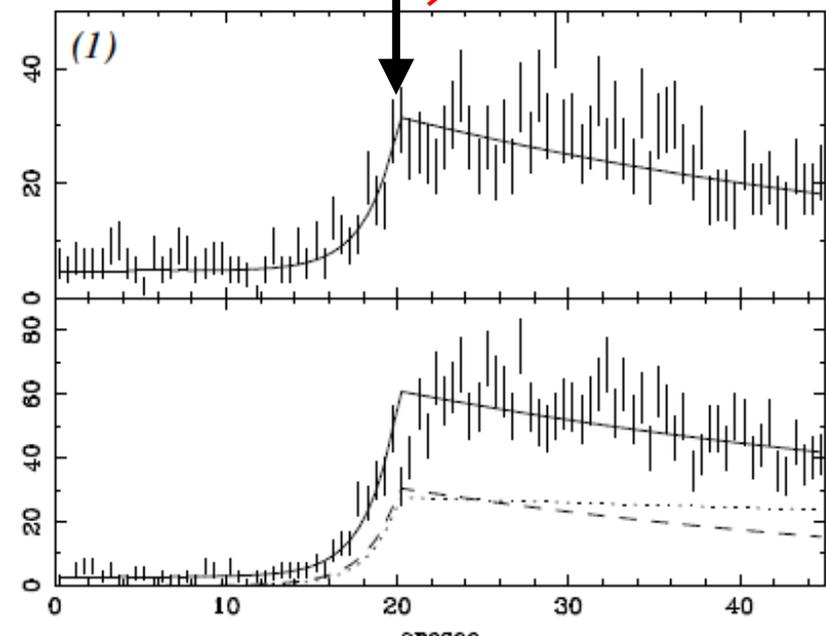
Bamba et al. (2002)

SN1006 shock analysis Bamba (2004)



Chandra

shock



解析結果まとめ

馬場さんのD論より借用

	Cas A	Kepler	Tycho	SN1006	RCW86
$t_{\text{acc}}/t_{\text{age}}$	0.088	0.42	0.26	0.34	1.16
Age limited case					
E_{max} (TeV)	...	16-31	4.8-18	22-69	41-172
B_d (μG)	...	10-150	32-52, 70-110	14-20	4-12
θ (deg.)	...	90	<10, 90	0-90	90
Loss limited case					
E_{max} (TeV)	10-36	50-54	16-17	26-54	41-172
B_d (μG)	139-305	72-85	82-99	23-85	4-12
θ (deg.)	<60	90	<10	<35	90

初めてのSNR磁場構造の見積もり

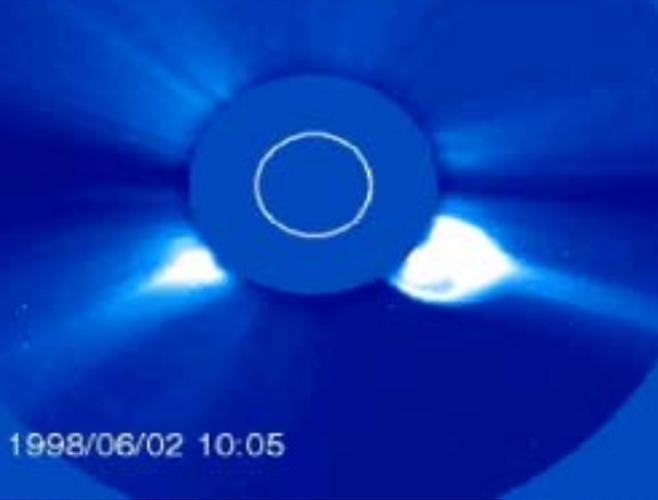
銀河内の平均的磁場
~3 μG × 4に比べて大きい

ほとんどのSNRが { age-limited
磁場は衝撃波面に垂直 } で説明可

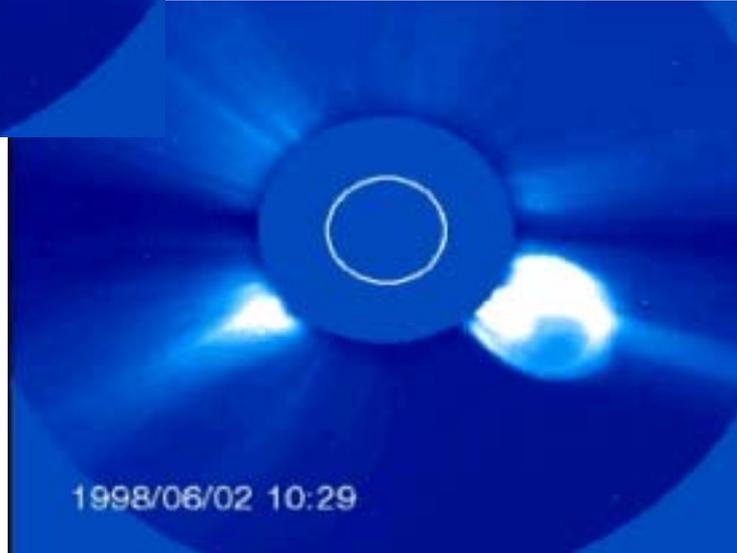
太陽面爆発(磁場エネルギー解放)



コロナ物質放出(CME)現象



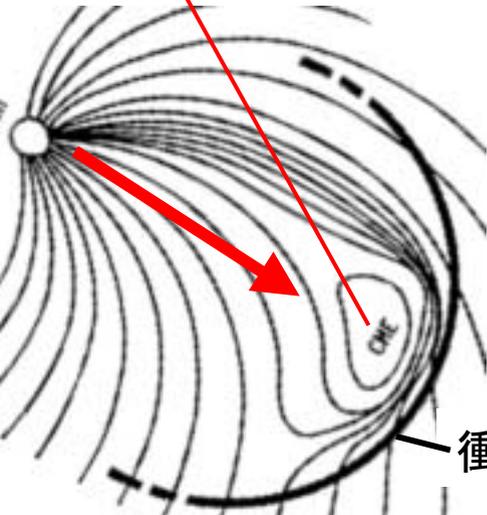
1998/06/02 10:05



1998/06/02 10:29

CMEのうち、高速なものは音速を超え、その前面に衝撃波を形成する

爆発に伴って放出されたコロナ物質



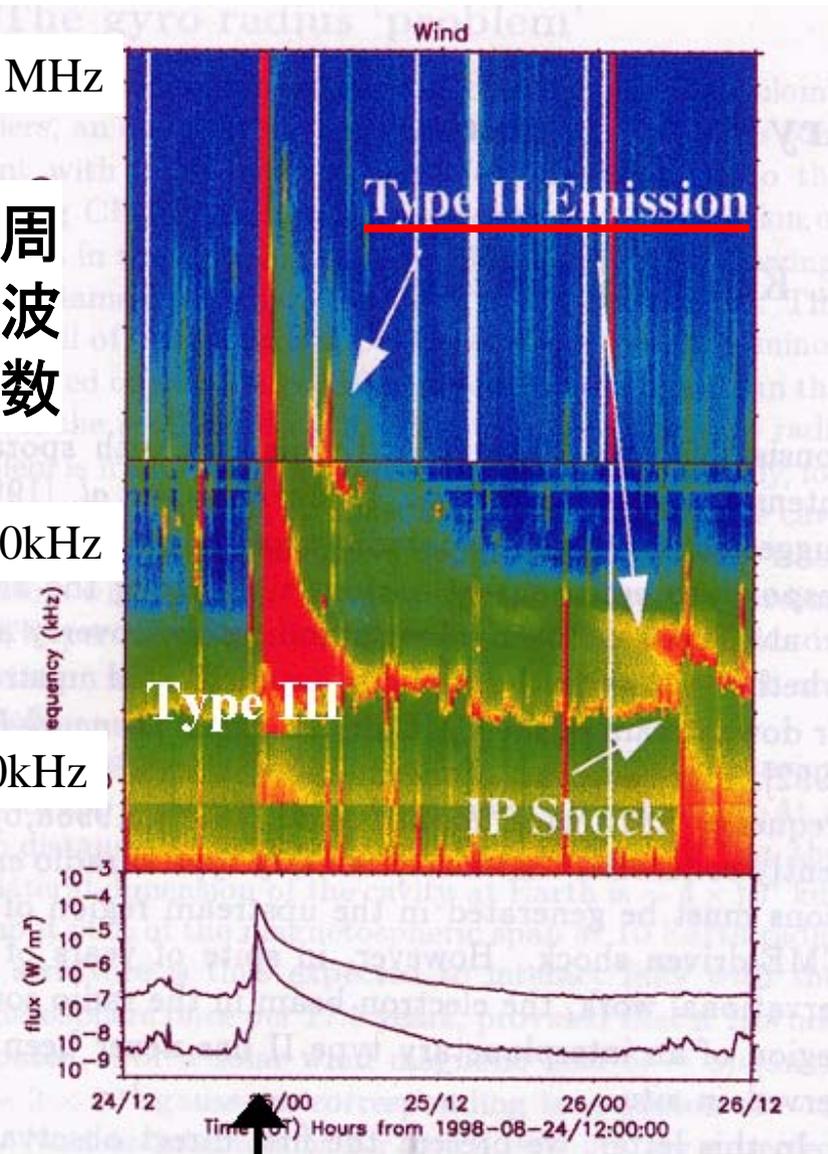
衝撃波



1998/06/02 11:27

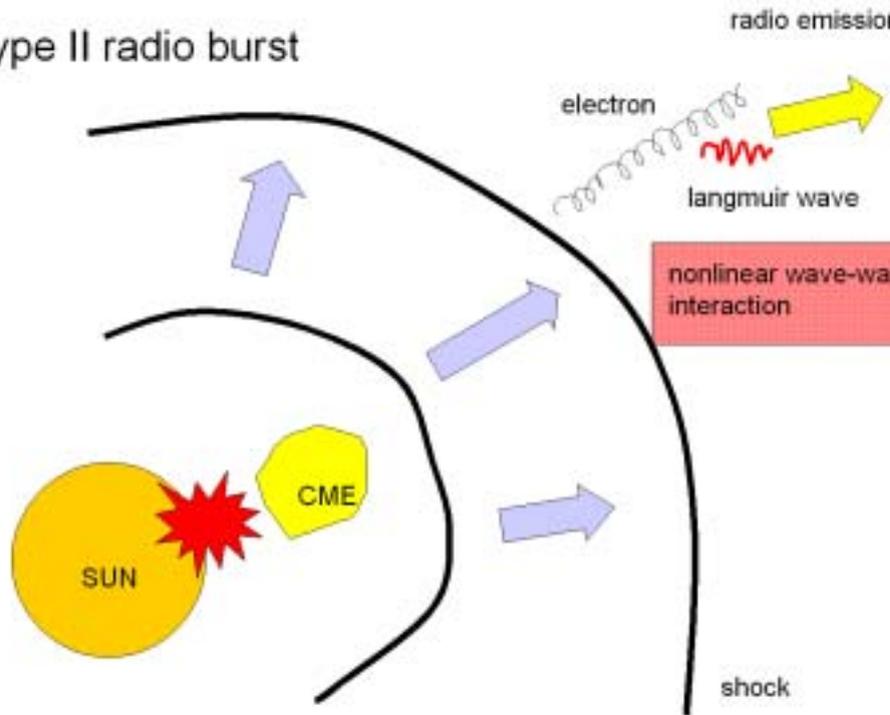
Type 2 event: 1998 August 24-26

WIND (Bale et al., GRL 1999)



衝撃波による電子の加速

Type II radio burst



フレア発生後数分から10分後に始まる。

メートル波からデカメートル波帯で、ゆっくり振動数帯
下げていく。

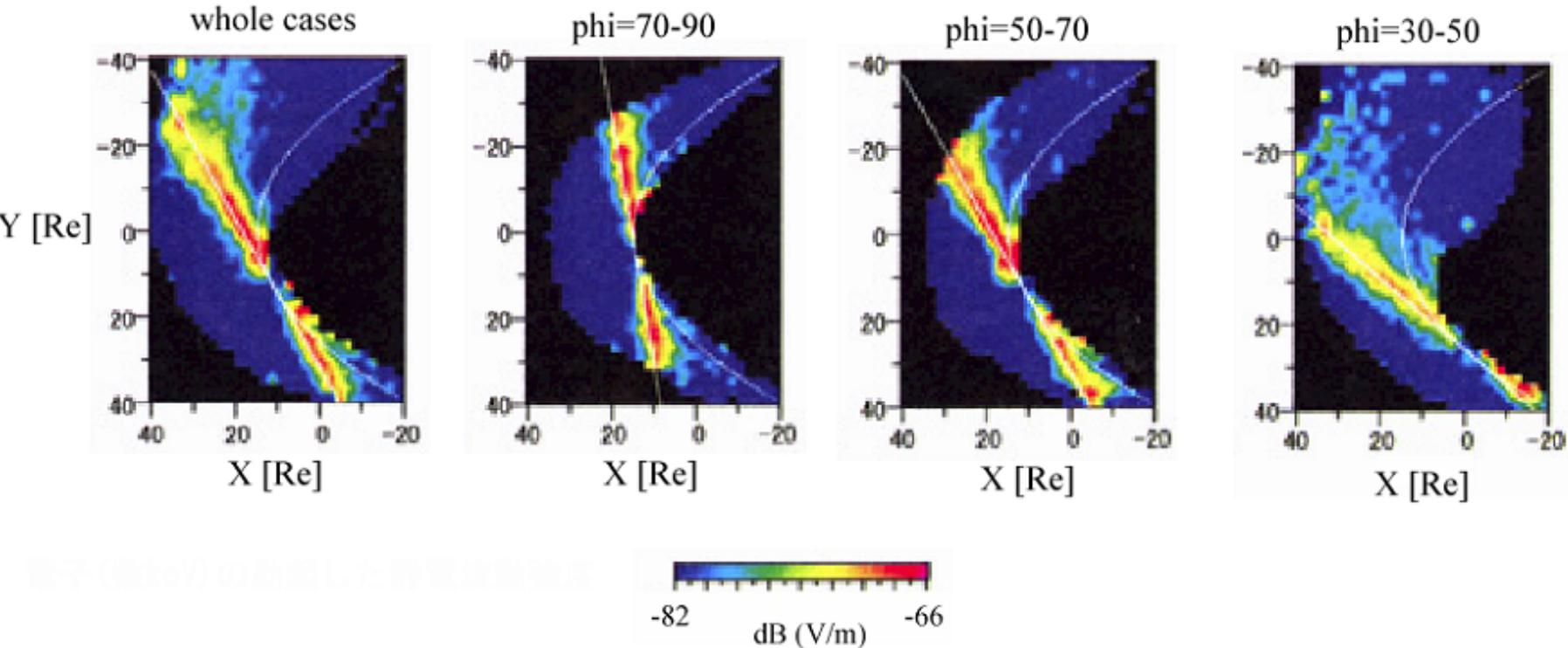
フレアに伴う衝撃波前面で発生するプラズマの波に
因する。

太陽からの距離に依存してプラズマ密度が減少する
ために、振動数帯が変化する。

衝撃波で作られた電子ビームが二流体不安定よりラン
ア波を引き起こすのが契機

Kasaba et al., (JGR, 2000 Jan)

plasma waves and backstreaming electrons in the foreshock region

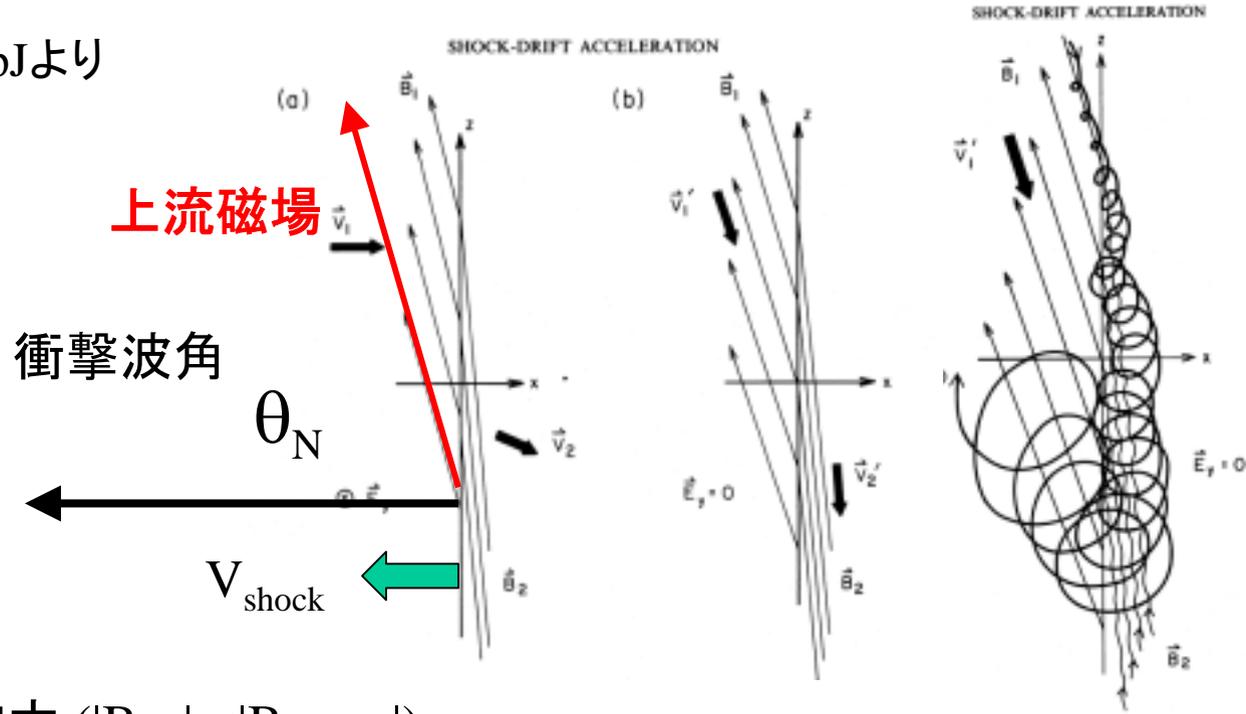


地球のBow shockにおけるType II 電波バーストの対応現象
 電子ビーム生成→ラングミュア波励起→電波への変換

これらの電子ビーム生成には衝撃波ドリフト加速が寄与している

図はChiueh (1989) ApJより

⊗
 $E = -V \times B$
 衝撃波面法線ベクトル



衝撃波面での磁場増大 ($|B_{UP}| < |B_{DOWN}|$)

- ... 粒子にmagnetic mirror forceを及ぼす
- ... その結果、粒子は $-V \times B$ 電場方向にドリフトして余分な加速を受ける

単なる壁による反射に伴う運動量増加 ... $2mV_{shock}$
 ドリフトによる加速を含めた運動量増加... $2mV_{shock}/\cos \theta_N$

$\theta_N \sim 90^\circ$ に近いときこの効果はきわめて大
 $1/\cos \theta_N \gg 1$

衝撃波ドリフト加速 ... 種々のサーフィン加速の原型

共通点: 粒子を衝撃波面にできるだけ長く捕捉し、その間に
- $V \times B$ 電場方向にドリフトさせてエネルギーを獲得させる。

衝撃波ドリフト加速

粒子を衝撃波面に沿って捕捉する力
... magnetic mirror force (*),(**)

古典的サーフィン加速

(Mizuno, Shapiro, Ohsawa, ...)

... 衝撃波面法線方向に働く
静電場(イオンのみ有効)

最近のサーフィン加速

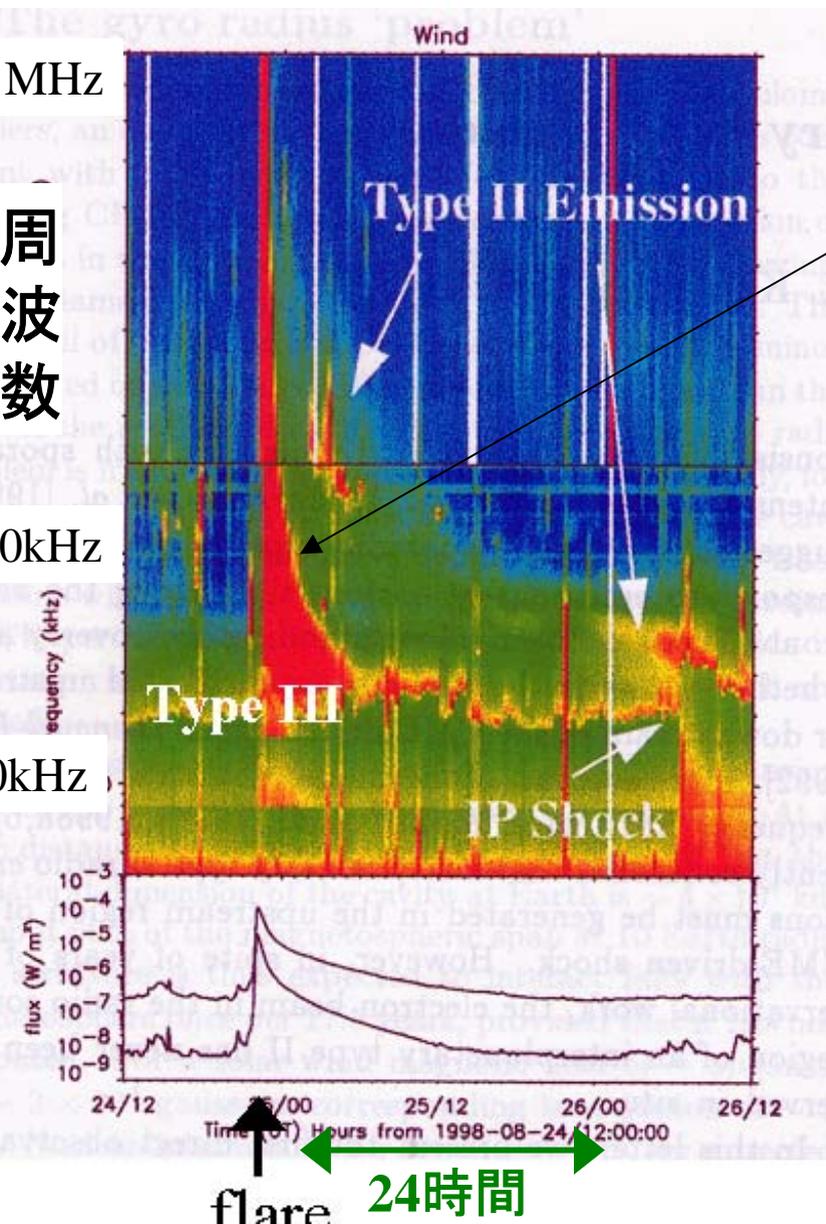
(Hoshino and Shimada, ...)

... 衝撃波遷移領域に励起された
大振幅静電波ソリトンによる
静電場(電子に有効)

(*) mirror forceは弱いので粒子はたかだかもとの
エネルギーの数倍～十数倍までしか加速できない。

(**) bow shockでは衝撃波ドリフト加速によってイオンの加速も
生じている(数～十数keVのイオンビーム生成)

WIND (Bale et al., GRL 1999)



Type 3 event

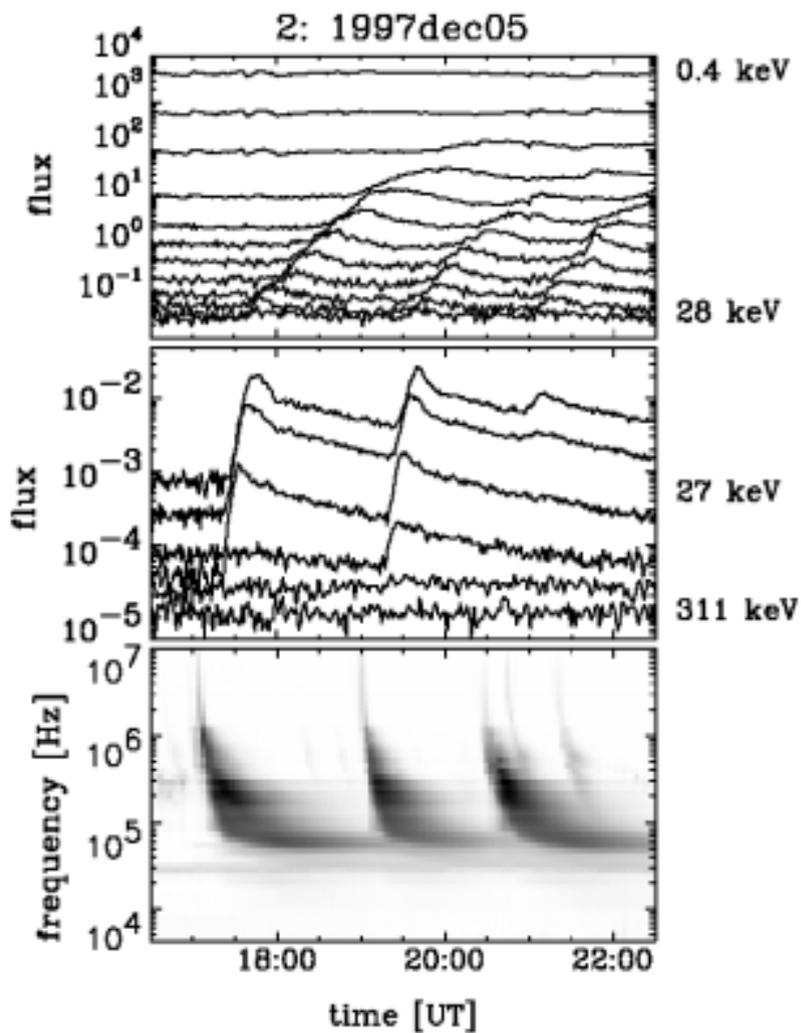
Type 2型電波バーストに先行し
ずっと速い周波数ドリフトをもつ



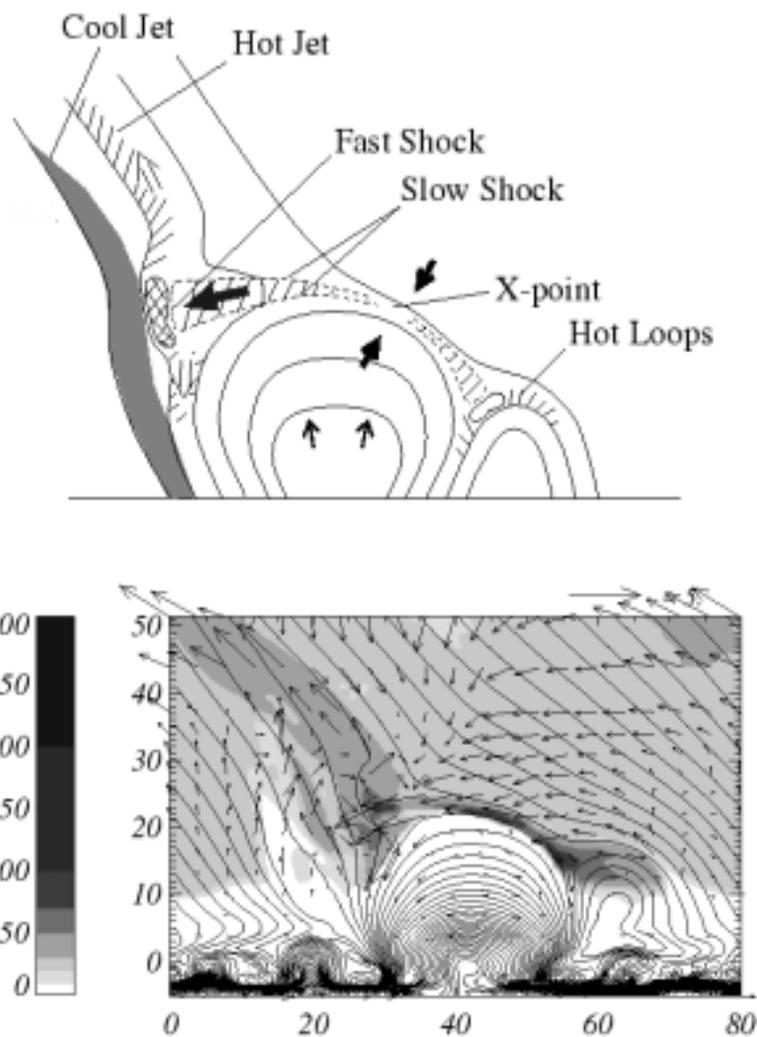
電波放射メカニズムがラングミュア
振動励起を經由して起こることは
Type 2と似ているが、電子は衝撃波
ではなく磁気リコネクションに起源を
持つと考えられている

reconnection in the lower corona -> electron acceleration (10-100 keV)
-> type 3電波バースト

Krucker et al. (1999)



Shibata and Yokoyama (1996)

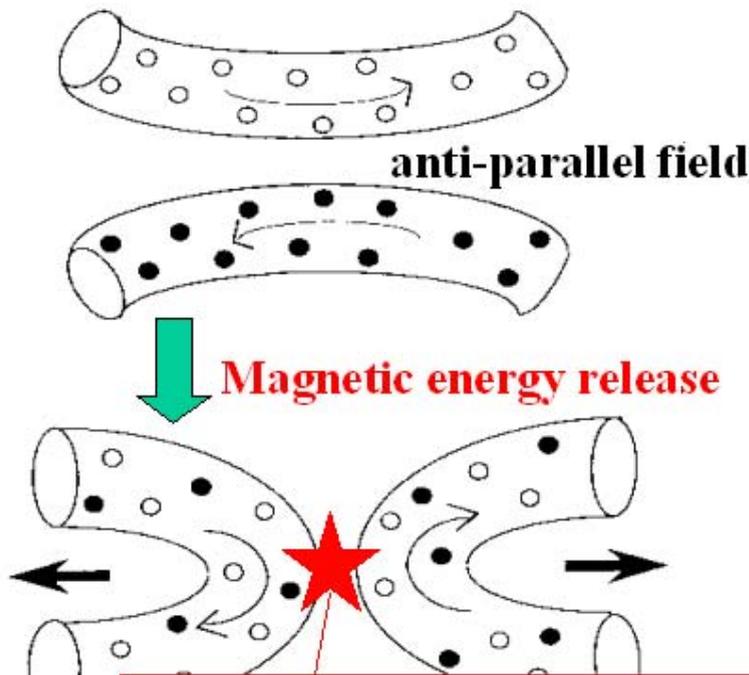


Reconnection

Solar flares

magnetosphere

Laboratory/fusion plasmas



University of Tokyo Symposium in 2000 on **Magnetic Reconnection** in **Space and Laboratory Plasmas**

at Sanjo-Kaikan, University of Tokyo
Tokyo, Japan Feb. 29 - Mar. 4



Chairpersons:

Y. Ono, K. Shibata, T. Terasawa

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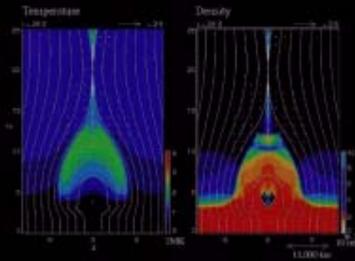
M. Hoshino, R. Matsumoto, T. Yokoyama
A. Ejiri, T. Itagaki, T. Kosugi,
H. Kurokawa, T. Mukai, T. Shimizu,
Y. Takase, M. Ugai, Z. Yoshida

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More about SEP (solar energetic particles)

Ions vs. electrons

衝撃波加速の標準理論: Diffusive Shock Acceleration Blandford and Ostriker (1978)

THE ASTROPHYSICAL JOURNAL, 221:L29-L32, 1978 April 1

PARTICLE ACCELERATION BY ASTROPHYSICAL SHOCKS

R. D. BLANDFORD AND
California Institute of Technology

J. P. OSTRIKER
Princeton University Observatory

$$\frac{\partial f}{\partial t} + (\mathbf{u} \cdot \nabla)f - \nabla \cdot (D_{\parallel} \mathbf{n} \mathbf{n} \cdot \nabla f) = \frac{1}{3}[\nabla \cdot \mathbf{u}] \left[\frac{\partial f}{\partial \ln p} \right]$$

or

$$(1a)$$

$$u \frac{\partial f}{\partial x} - \frac{\partial}{\partial x} \left[D_{\parallel} \cos^2 \theta \frac{\partial f}{\partial x} \right] = \frac{1}{3}(u_+ - u_-) \delta(x) \left[\frac{\partial f}{\partial \ln p} \right]$$

.....

$$(1b)$$

This equation must be solved on either side of the shock and the solutions joined by imposing continuity [by $\delta(x)$] of the distribution function f and the particle energy flux, at a given energy, normal to the shock, $-u \partial f / \partial \ln p^3 - \kappa \nabla f$ [to 0 (u_-/v)], where $\kappa = D_{\parallel} \cos^2 \theta$.

In a stationary solution, the flux $u f - \kappa \nabla f$ must be constant on either side of the shock; f will approach asymptotic values $f_-(f_+)$ as the distance from the shock $x \rightarrow -\infty$ ($x \rightarrow +\infty$). As $\kappa > 0$, the solution behind the shock must be $f = f_+$, $x \geq 0$, whereas ahead of the shock

$$f = f_- + (f_+ - f_-) \exp \left[u_- \int_x^{\infty} dx' / \kappa_-(x') \right],$$

$x \leq 0$. However, independent of the variation of κ_- we can relate f_+ , f_- , using the junction conditions to obtain $df_+/d \ln p^3 = (f_+ - f_-)u_-/(u_+ - u_-)$, of which the solution is

$$f_+(p) = q p^{-q} \int_0^p f_-(p') p'^{(q-1)} dp', \quad (2)$$

with $q = 3r/(r-1)$. That is to say, incident cosmic rays of space density n_- and momentum p_0 are Fermi accelerated by the shock to give a power-law distribution $f_+(p) = n_- p_0^{(q-3)} \Theta(p - p_0) / 4\pi(q-3)p^{-q}$. If $f_- \propto p^{-s}$ with $s < q$, then $f_+ = q/(q-s)f_- \propto p^{-s}$. However, if $s < q$, lower-energy particles will be accelerated to give $f_+ \propto p^{-q}$, where the coefficient is determined by the number of particles for which Fermi acceleration is more important than thermalization by collisionless processes behind the shock and ionization losses. For particles accelerated in this way, the mean energy gain is $3/(5-2r)$, $r < 2.5$ for nonrelativistic particles and $3/(4-r)$, $r < 4$ for ultrarelativistic particles.

Monte-Carlo simulation

A shock is at $X=0$.
plasma velocities
are

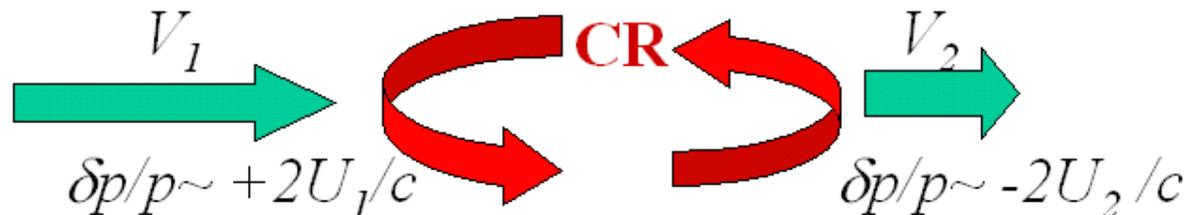
$$U_1=1 \quad (X<0),$$

$$U_2=0.25 \quad (X>0).$$

particle velocities
are measured in
the shock rest
frame.

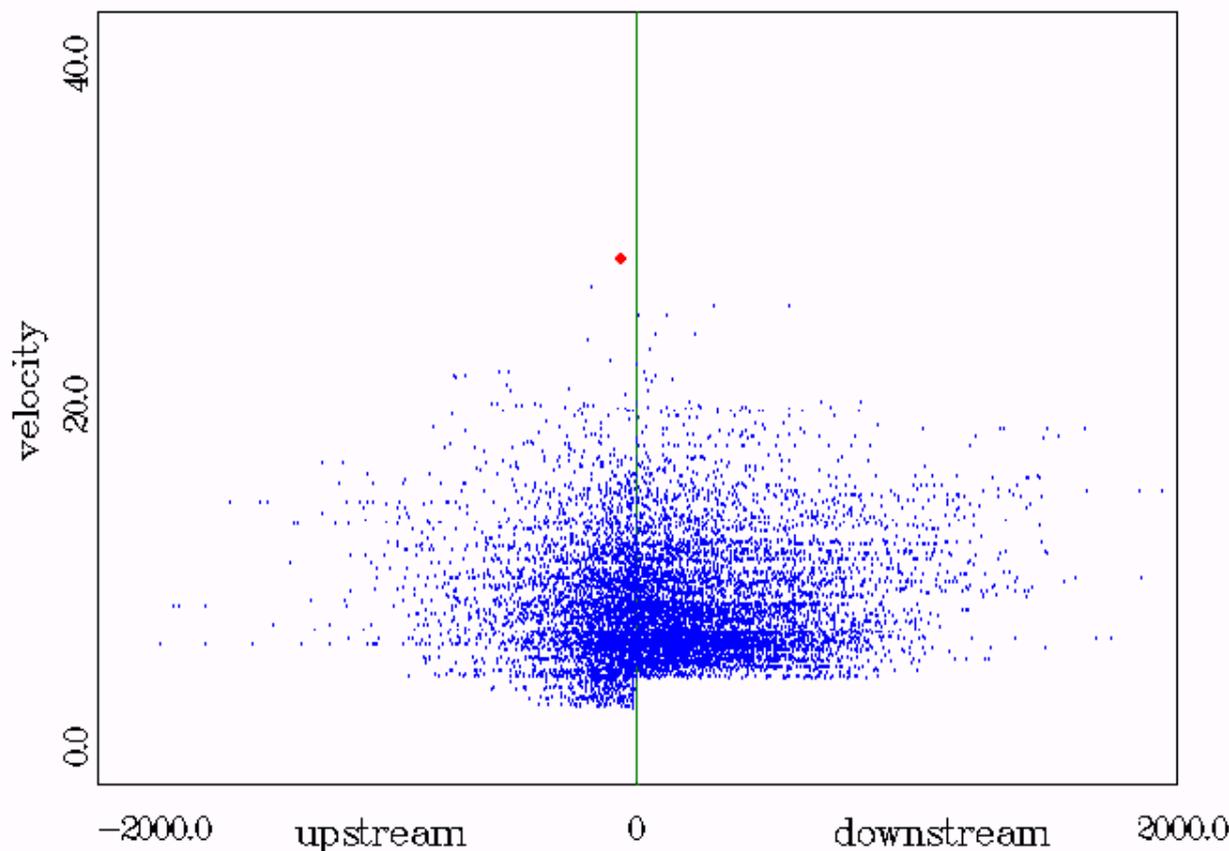
particles are
continuously
injected at $X=-10$
with $V_{inj}=5$.

head-on collision



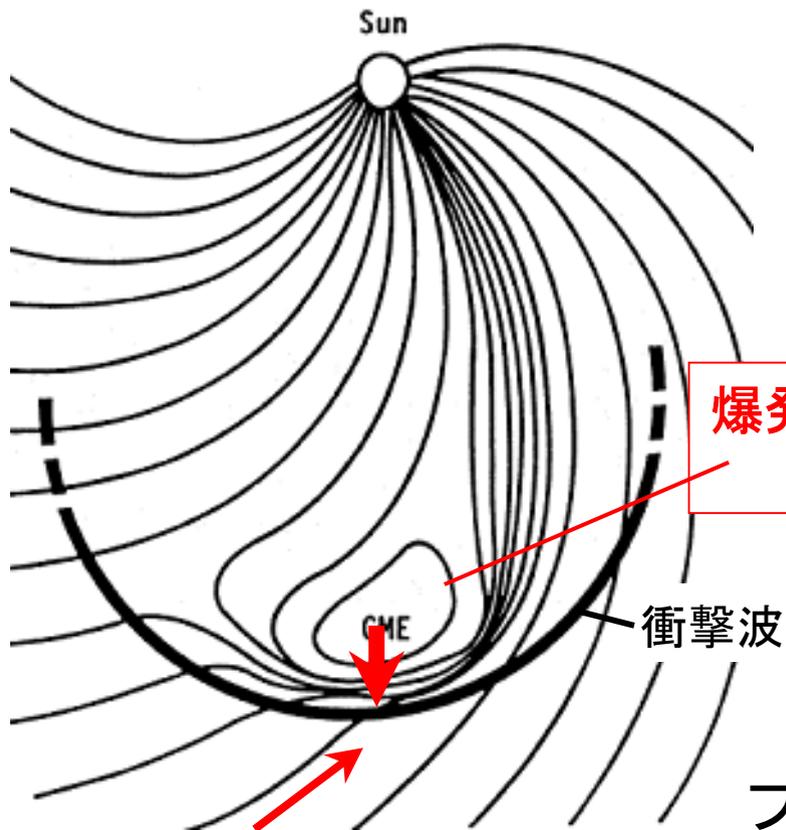
```
Umax Xmin Xmax Xshock Reomp  
1000 -2000.00 2000.00 0.00 4.00  
T= 502.00
```

```
taul taubeki dt Xini Vini Vmax BNKtfactor  
10.000 0.000 1.0000 -5.00 -5.00 100.00 8688.00000
```



太陽面爆発→衝撃波→粒子加速

(Reams, 1996)



爆発に伴って放出された
コロナ物質

衝撃波

2003/10/28の例

フレア → 地球への衝撃波到着

28日11時

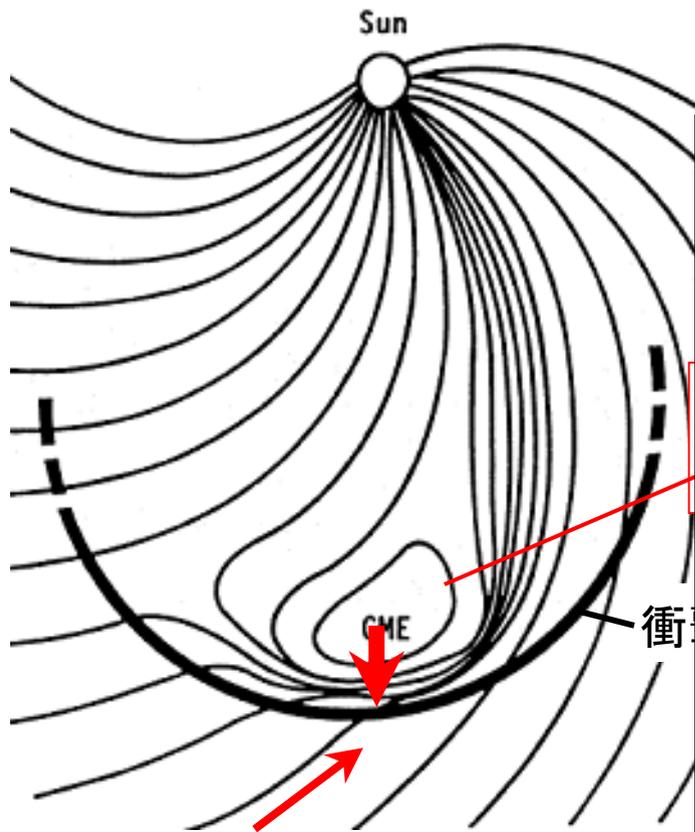
29日6時

衝撃波に伴う粒子加速
(数十～百MeVの陽子、ヘリウム、...)

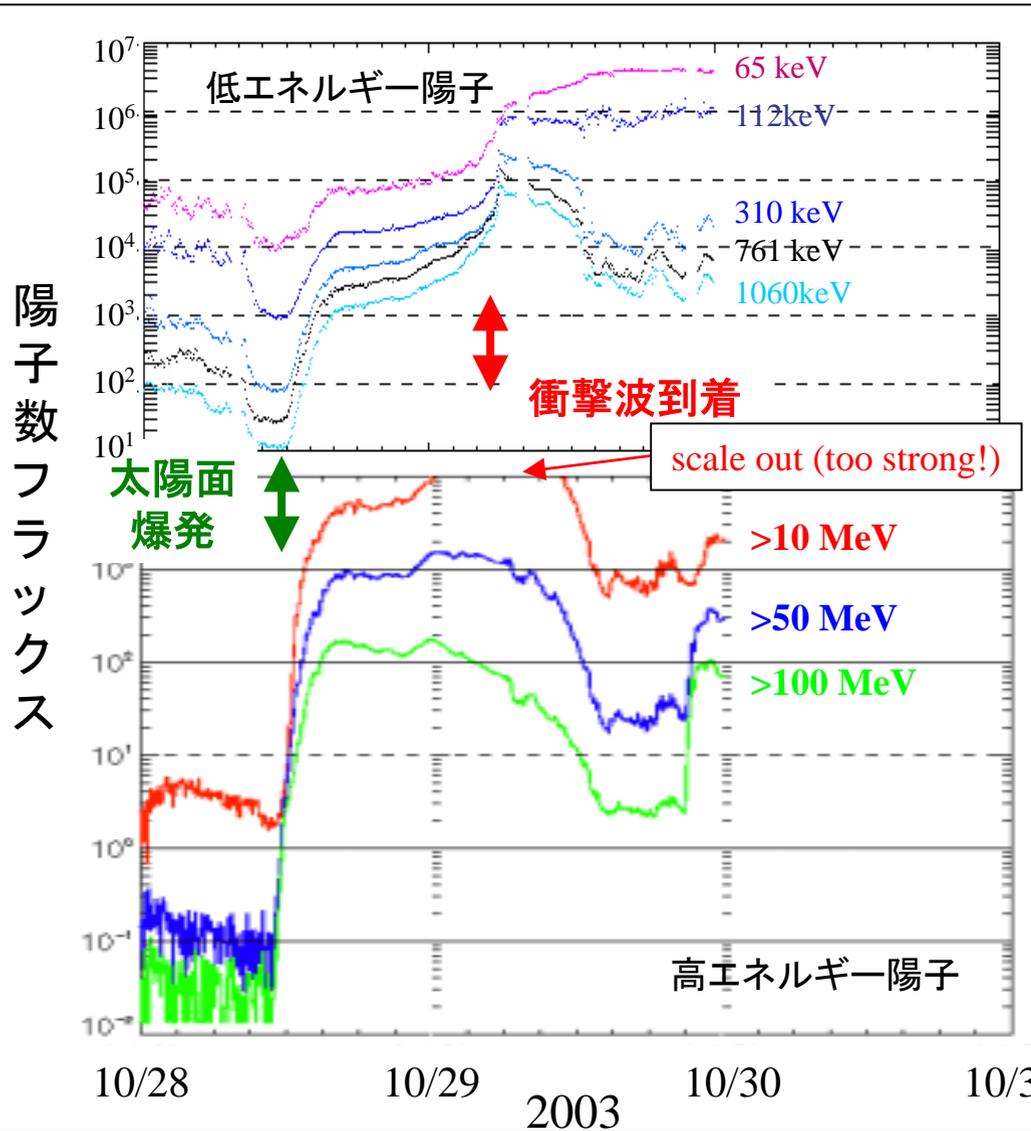
したがって平均速度は
1AU/19時間～2200km/s!

太陽面爆発→衝撃波→粒子加速

(Reams, 1996)



衝撃波に伴う粒子加速
(数十～百MeVの陽子、ヘリウム、...)



Solar Energetic Particles (>10MeV) / Largest 10 events in the 1967-2000 interval

courtesy of Dr. Watari (CRL)

ranking	date	maximum flux *
1	04 Aug 1972	86,000
2	24 Mar 1991	43,000
3	20 Oct 1989	40,000
4	15 July 2000	24,000
5	09 Nov 2000	13,300
6	21 Feb 1994	10,000
7	13 Aug 1989	9,200
8	01 Dec 1989	7,200
9	09 May 1992	4,600
10	30 Sep 1989	4,500

2003/10/28

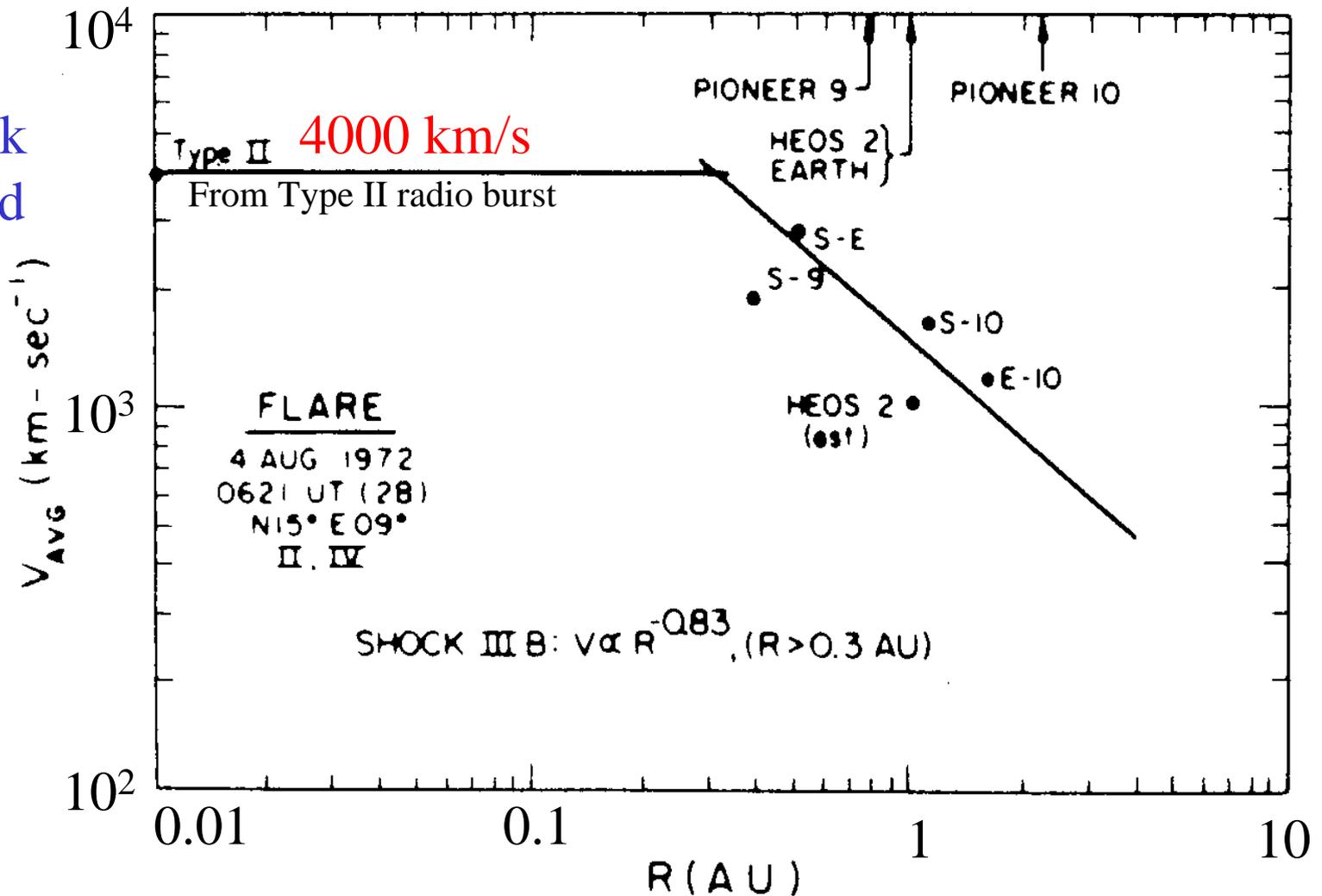
~30,000 sfu

* SEP flux unit= protons/(cm² sec str)

The Fastest Interplanetary Shock ever observed

August 1972 event

shock
speed



Smart & Shea, 1985

distance from the sun

Solar Energetic Particles (>10MeV) / Largest 10 events in the 1967-2000 interval

courtesy of Dr. Watari (CRL)

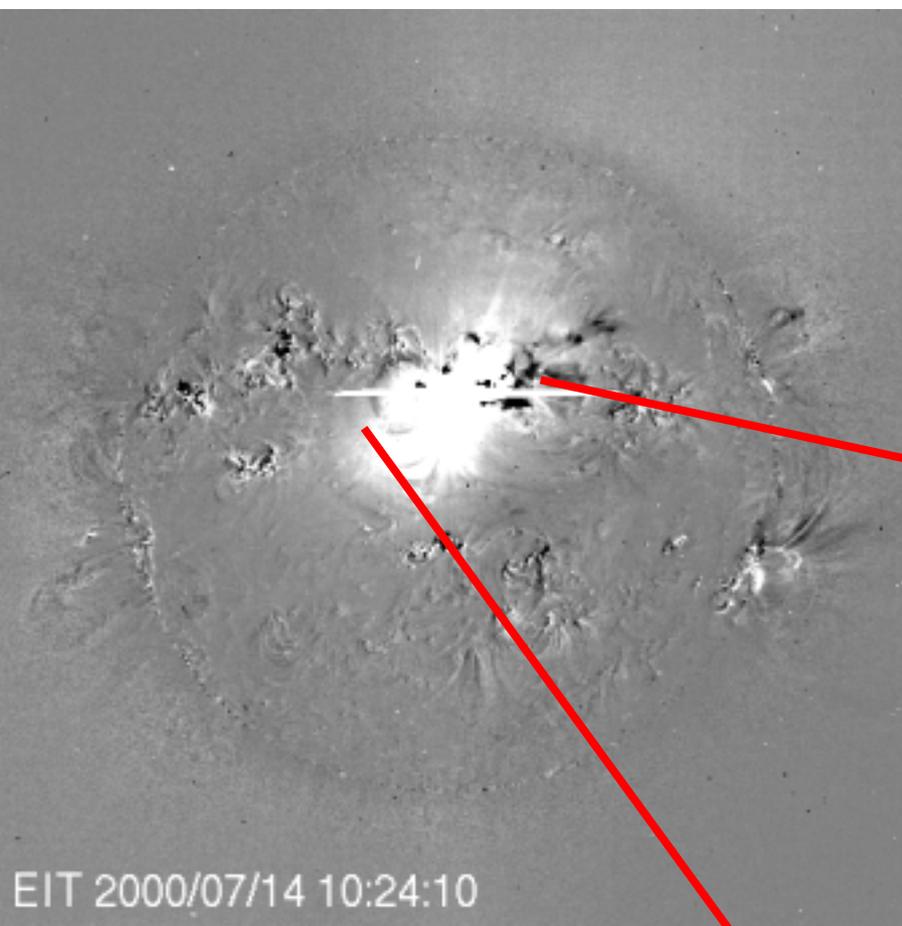
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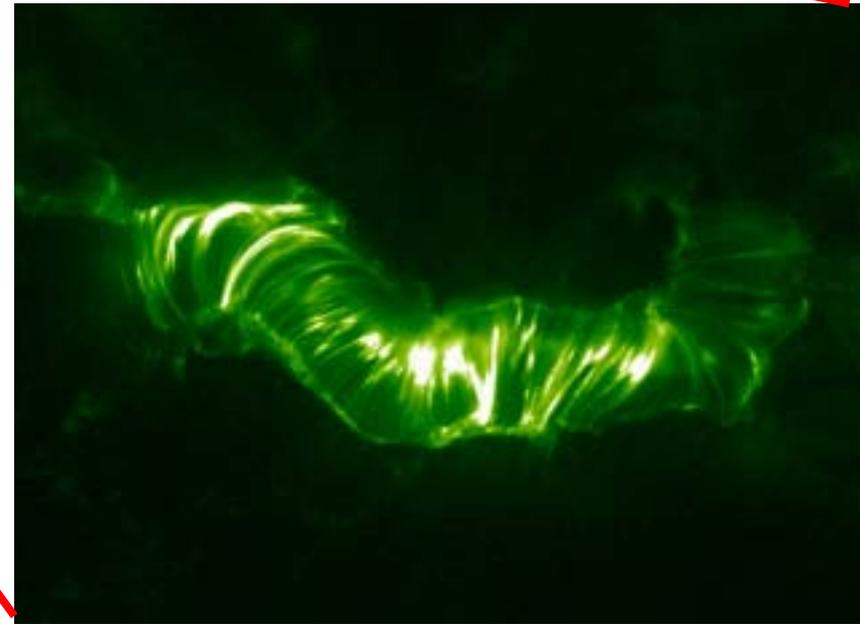
~30,000 sfu

* SEP flux unit= protons/(cm² sec str)

Bastille flare images 14 July 2000



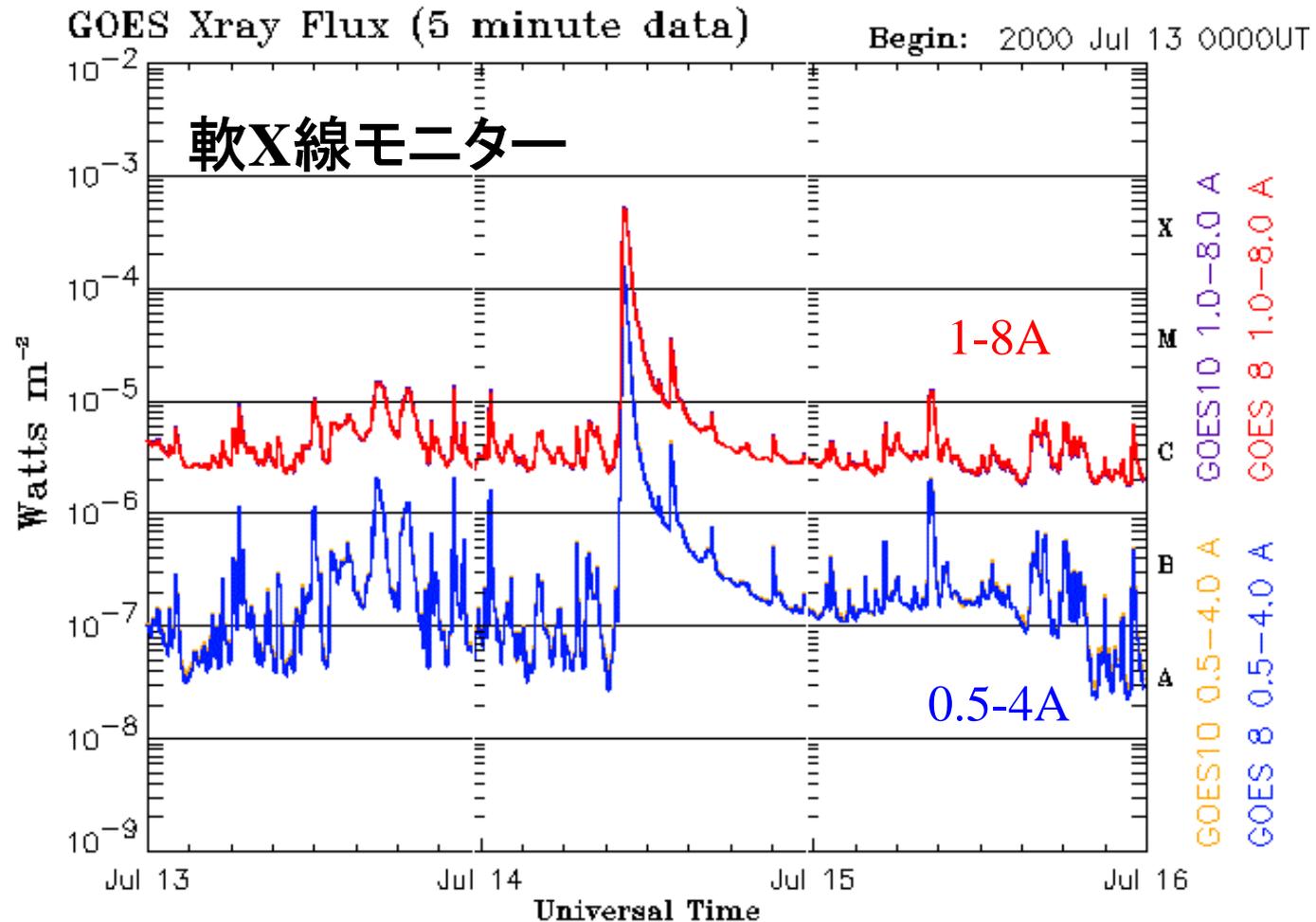
SOHO/EIT



Trace image

the Bastille-day solar storm

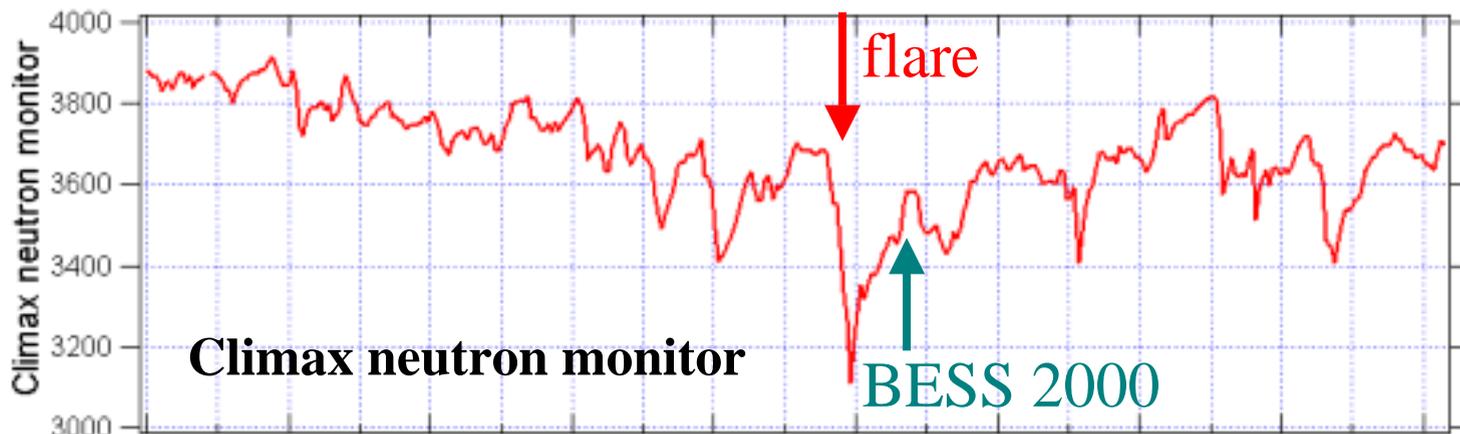
3B/X5.7 flare (N22W07) at 10:03 on 14 July 2000



Updated 2000 Jul 15 23:59:04

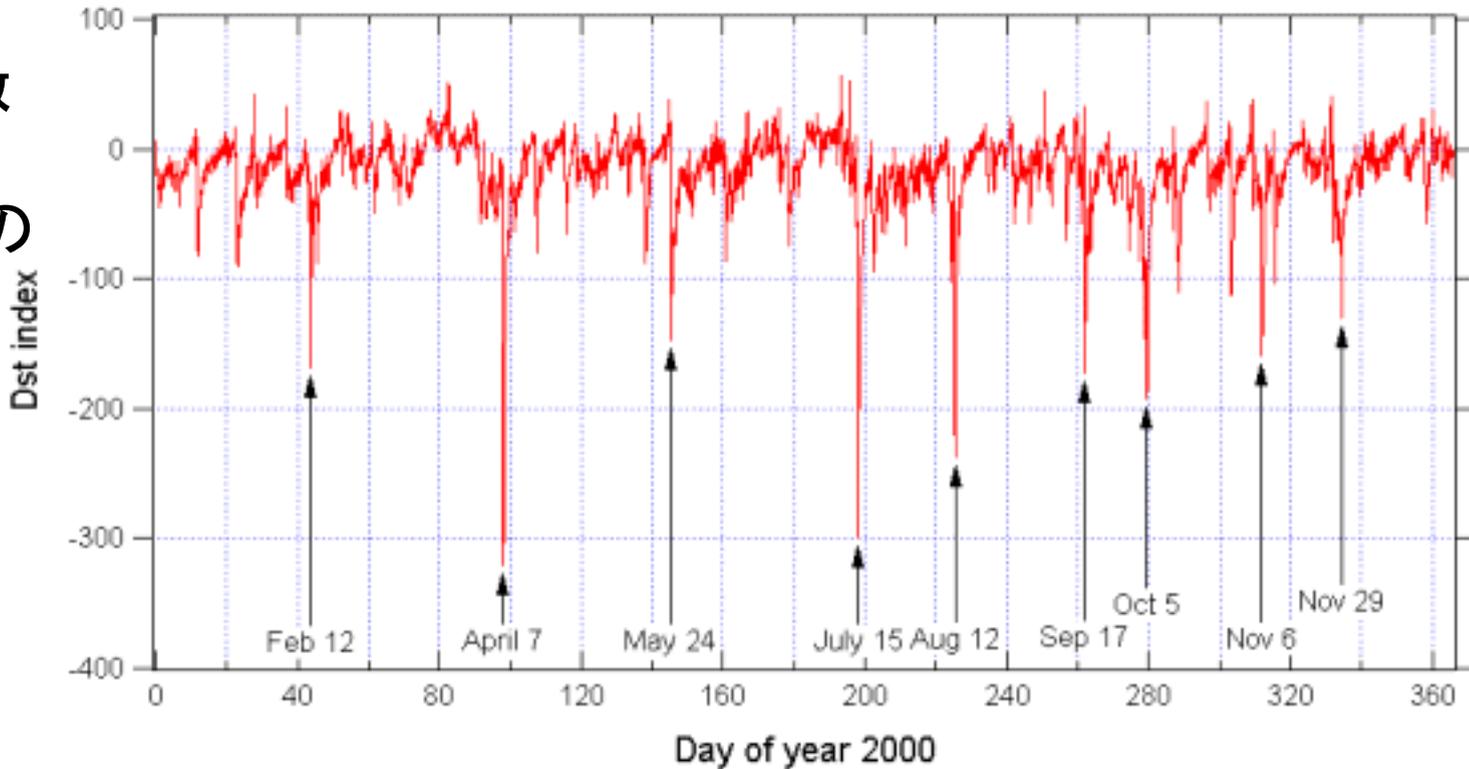
NOAA/SEC Boulder, CO USA

2000 solar activity (neutron monitor and Dst index)



Dst指数

磁気嵐の
強度





2000 Bastille day flare

2000/7/14

地球近傍の惑星間空間における
Geotail衛星観測 (bow shockの外)

Shock (フレアの28時間後に到着)

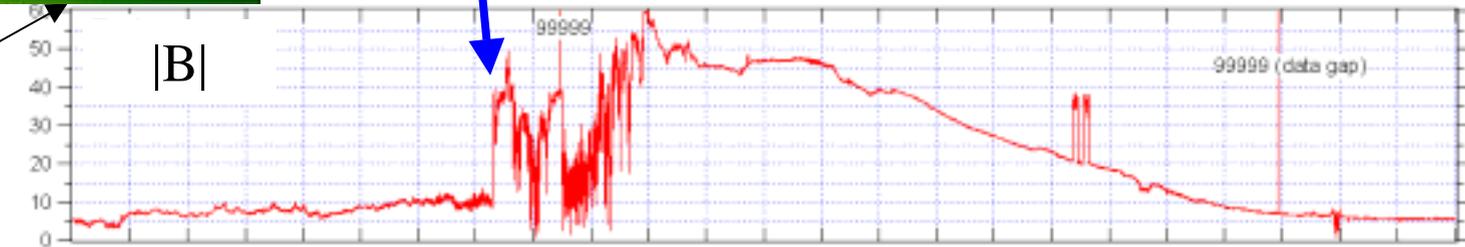
平均速度~1500km/s

15-16 July 2000 "Bastille solar storm"

Geotail/MGF

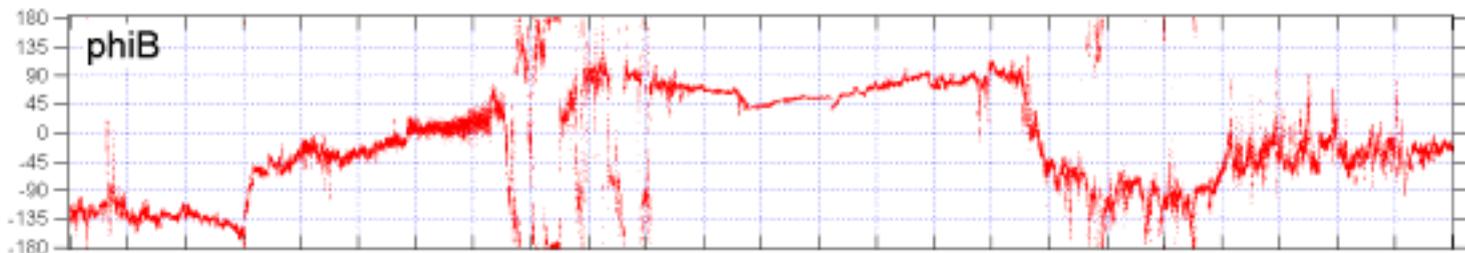
100μG

|B|



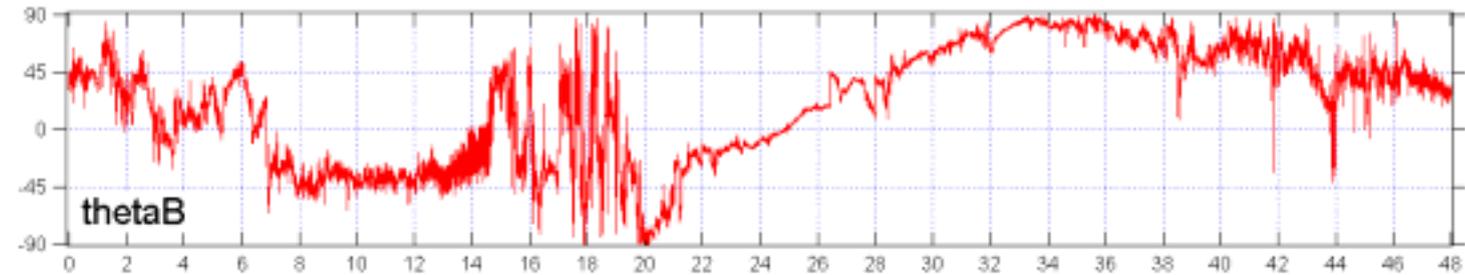
経度角

phiB



緯度角

thetaB



hours from 0 UT on 15 July 2000



2000 Bastille day flare

2000/7/14

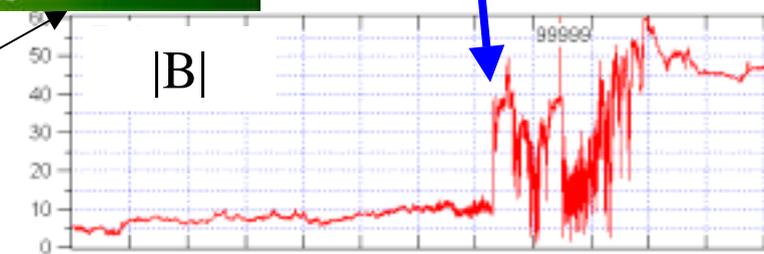
地球近傍の惑星間空間における
Geotail衛星観測 (bow shockの外)

Shock (フレアの28時間後に到着)

平均速度~1500km/s

15-16 July 2000 "Bastille solar storm"

1000μG

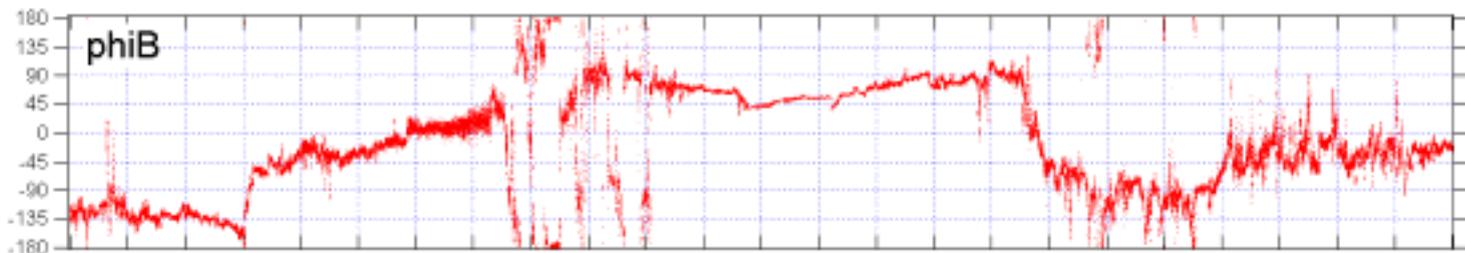


この衝撃波到来に伴う磁気嵐

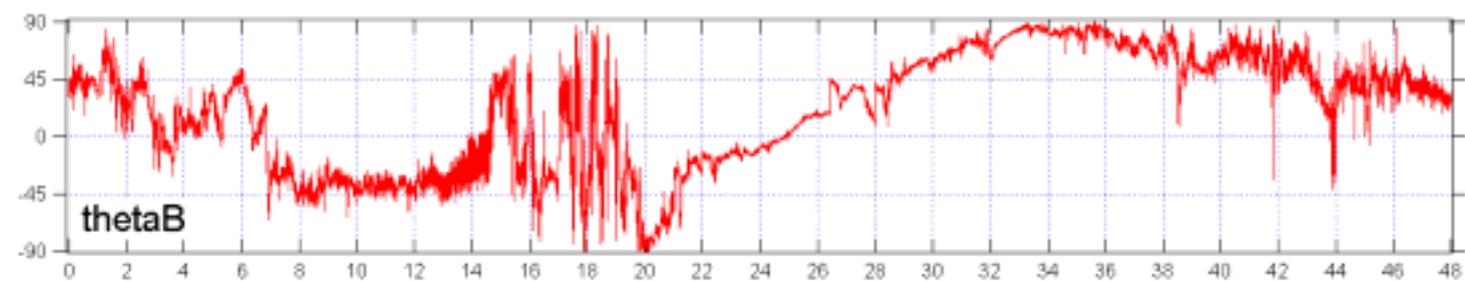


「ASCA」喪失の原因

経度角



緯度角



hours from 0 UT on 15 July 2000



2000 Bastiane day flare
この時間帯に注目
2000/7/14

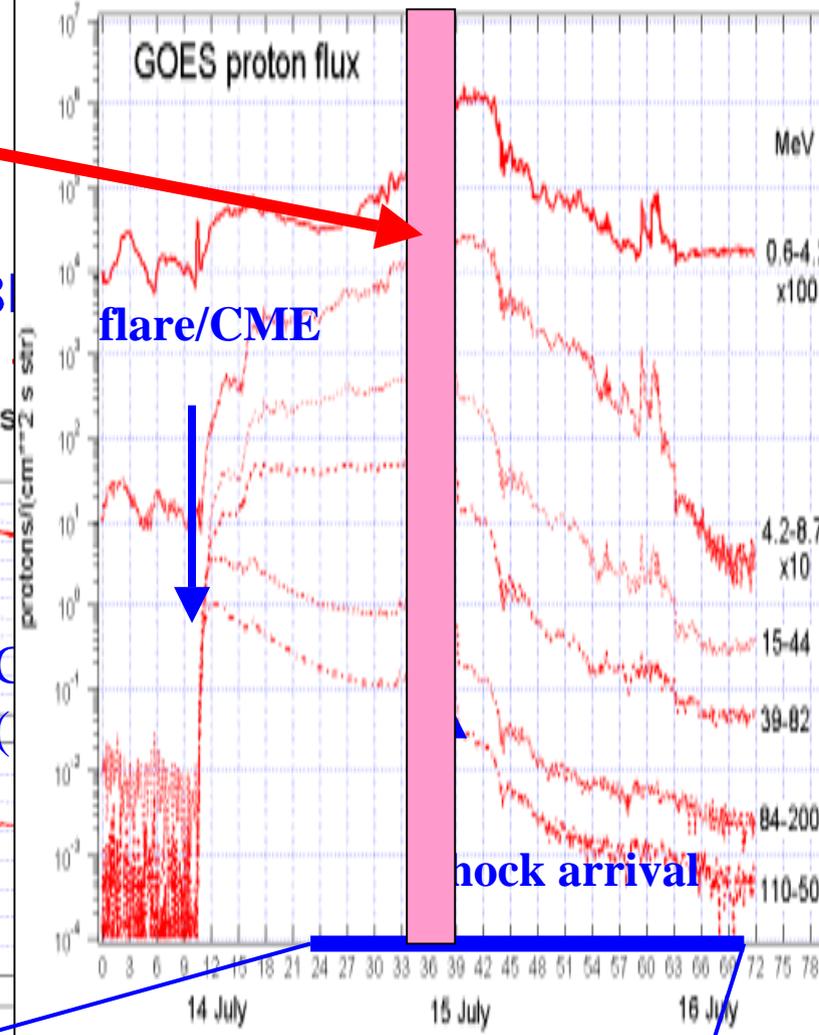
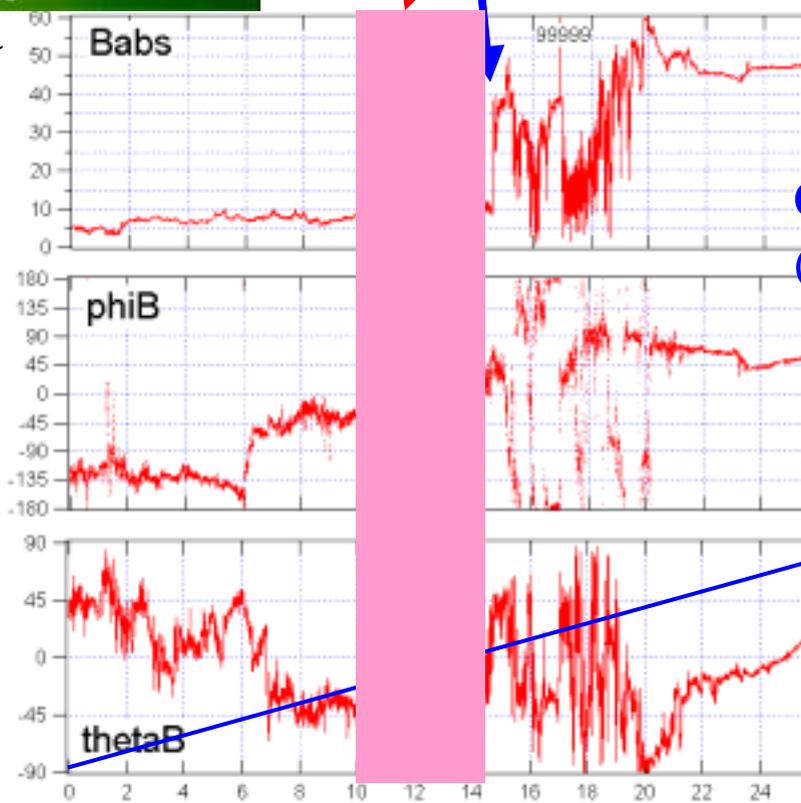
Shock (フレアの28)

15-16 July 2000 "Bas"

00 μ G

経度角

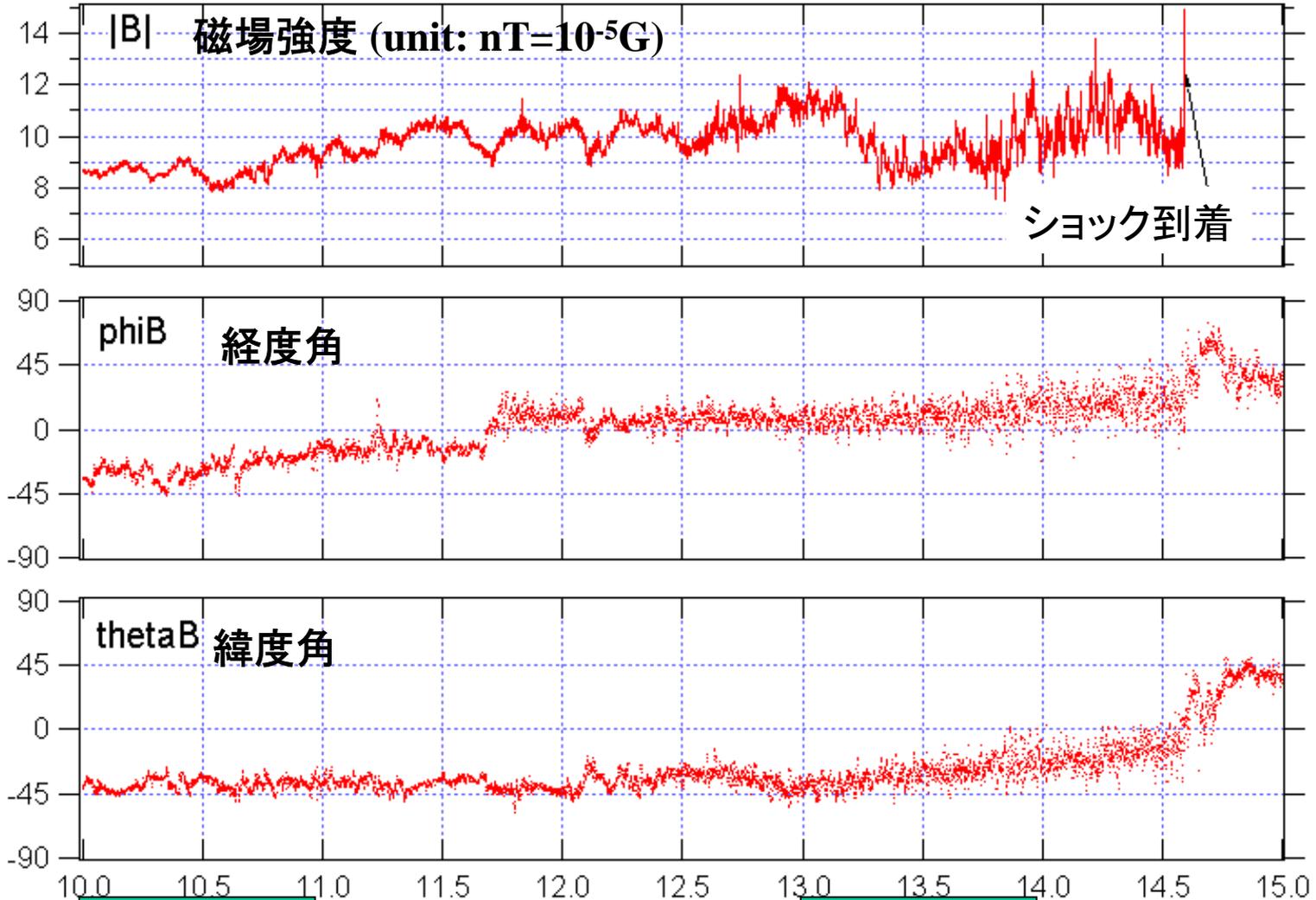
緯度角



hours from 0 UT on 15 July 2000

<~5x10² keV protonsと共鳴するアルフェン波の励起

Geotail/MGF (3 sec)



ショック到着4時間前
±30分

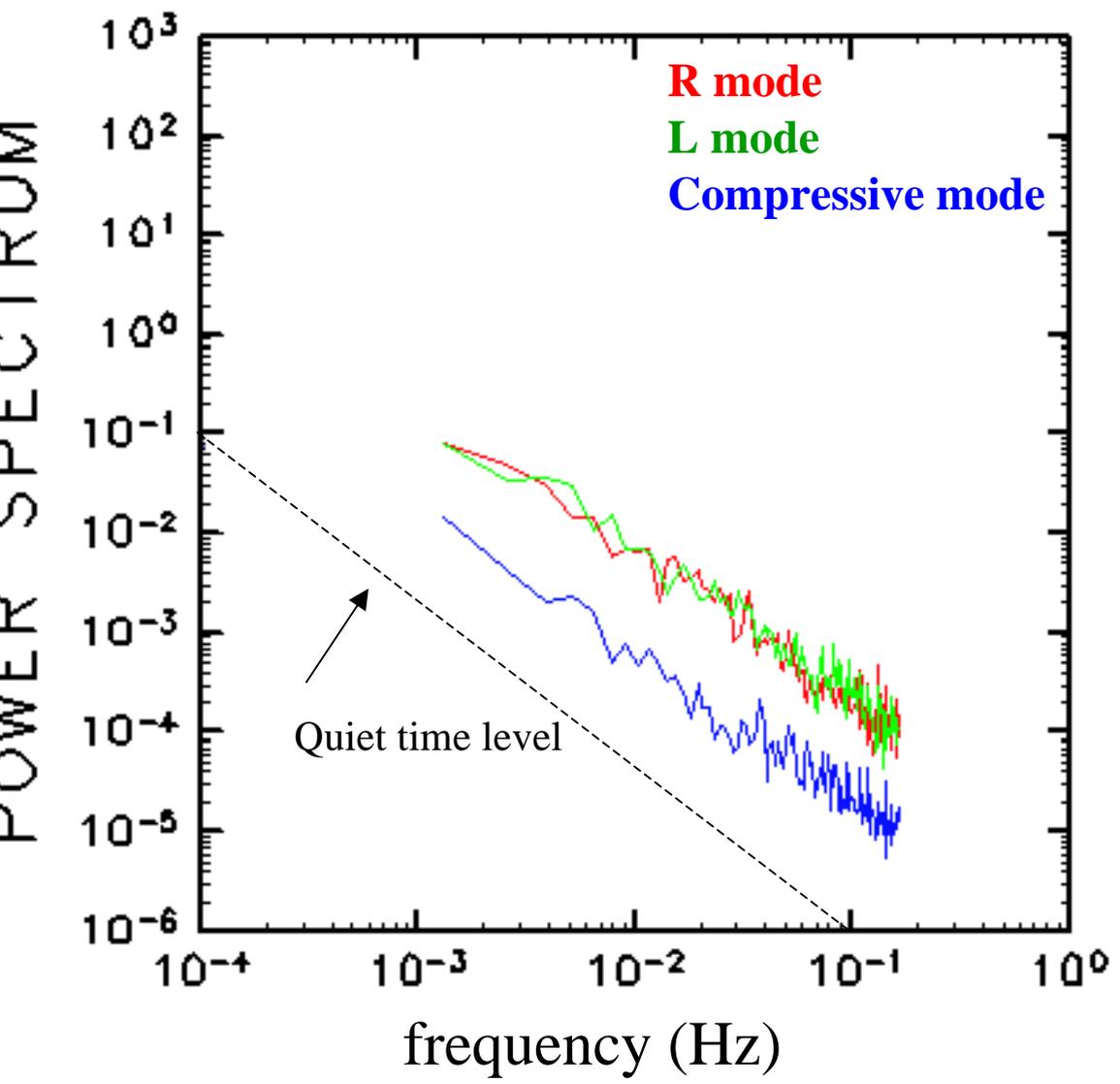
UT on 15 July 2000

1時間前
±30分

Power spectra of MHD turbulence (15 July 2000 event)

ショック到着4時間前±30分

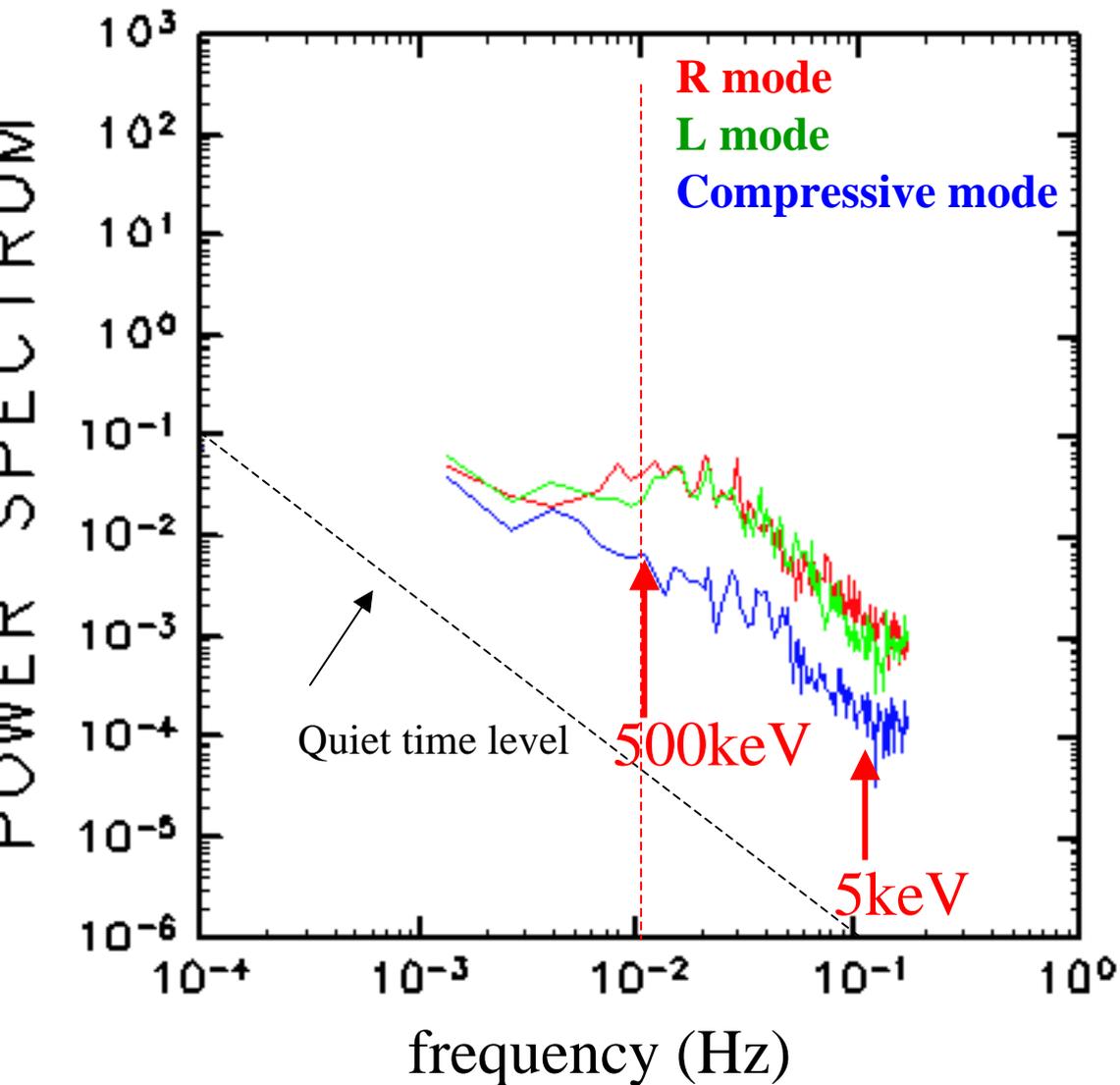
10:00-10:59



Power spectra of MHD turbulence (15 July 2000 event)

ショック到着1時間前±30分

13:00-13:59



Doppler shifted freq.

$$f \sim 10^{-2} \text{ Hz} = kV_{sw}/2\pi$$

$$k \sim 10^{-9} \text{ cm}^{-1}$$

gyro resonance condition

$$kw \sim \Omega_{ci} = 1 \text{ rad/sec}$$



$$w \sim 10^9 \text{ cm/sec}$$

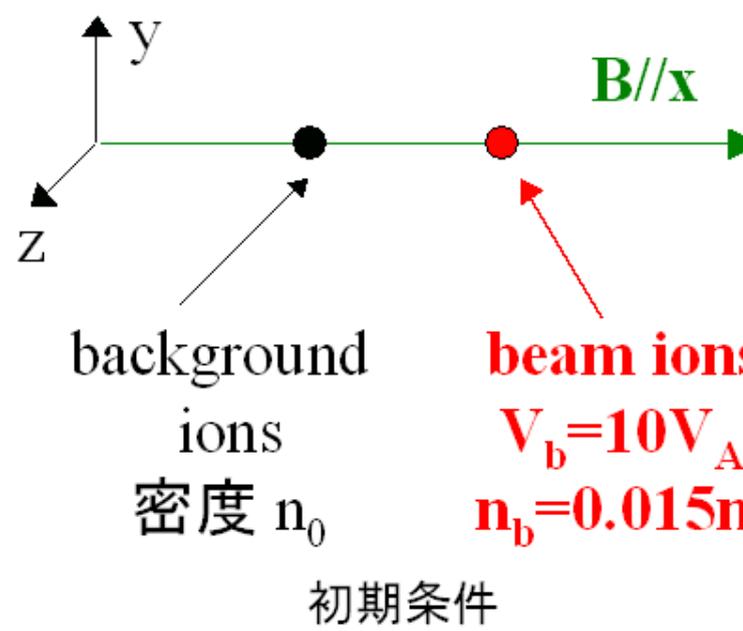
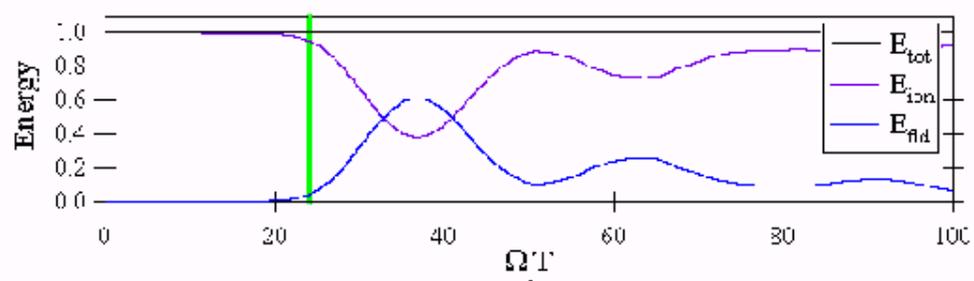
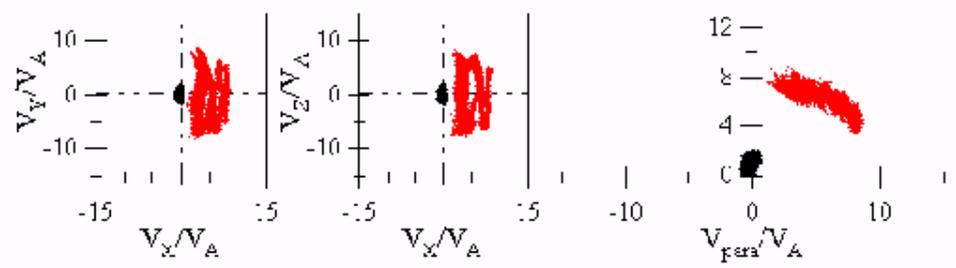
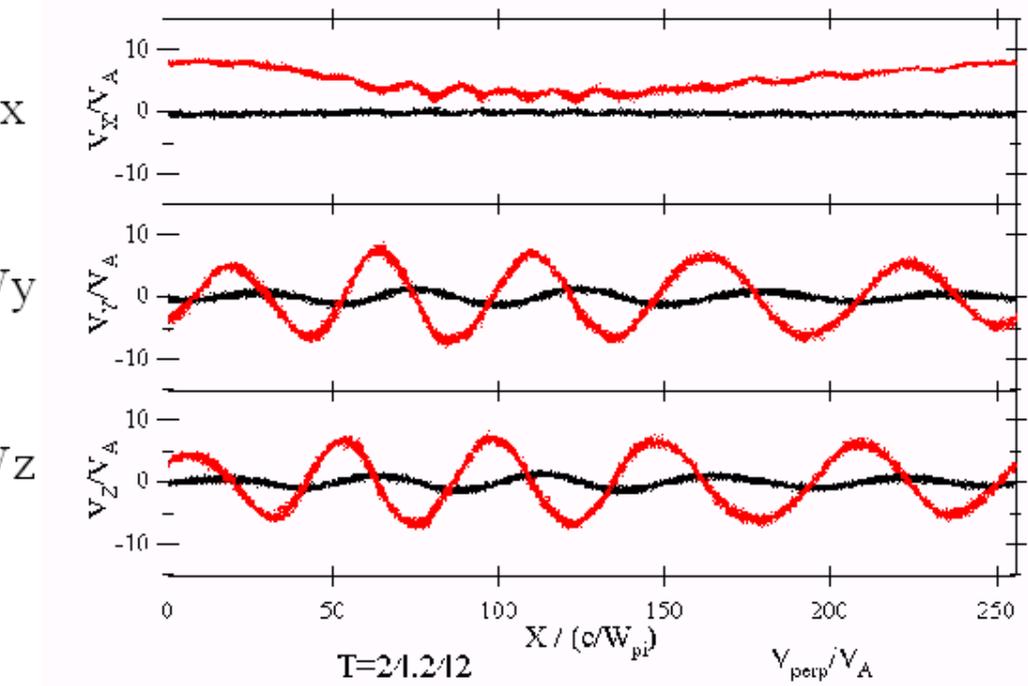


$$E \sim 500 \text{ keV}$$

波の励起: 準線形理論で説明

e.g. Kennel et al., 1986

イオンヒーム・サイクロトロン不安定性 (粒子シミュレーション by 岡)



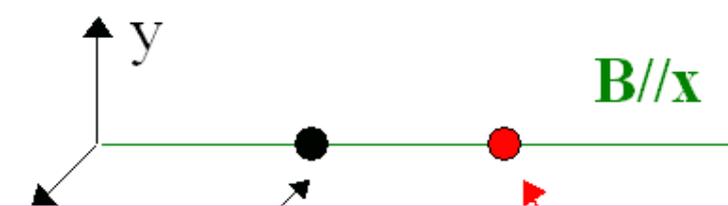
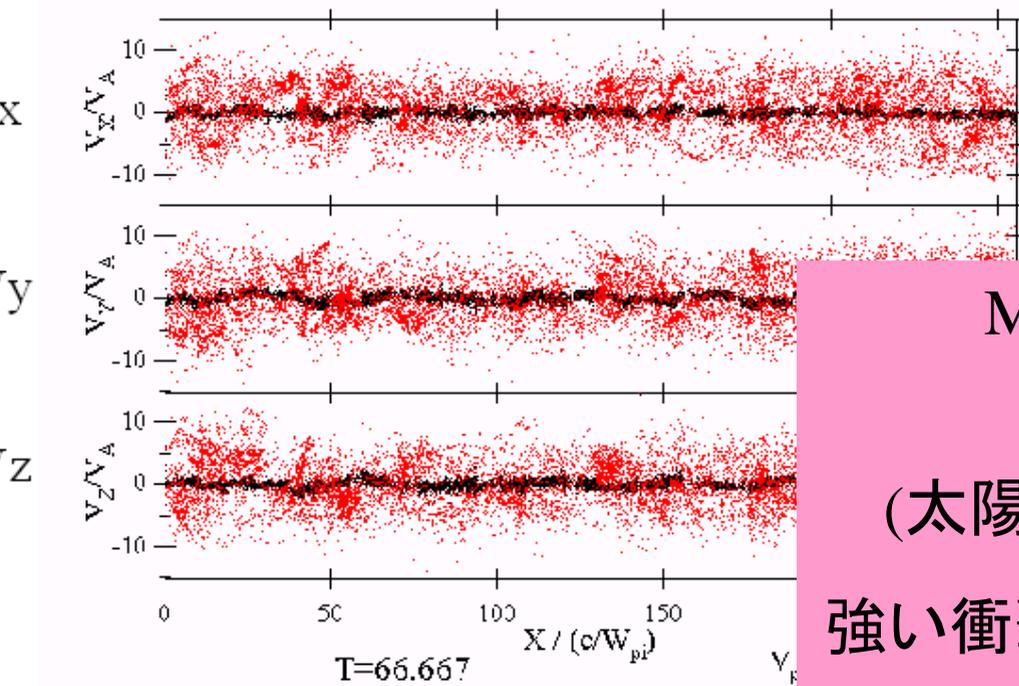
イオン・サイクロトロン周波数

サイクロトロン共鳴条件

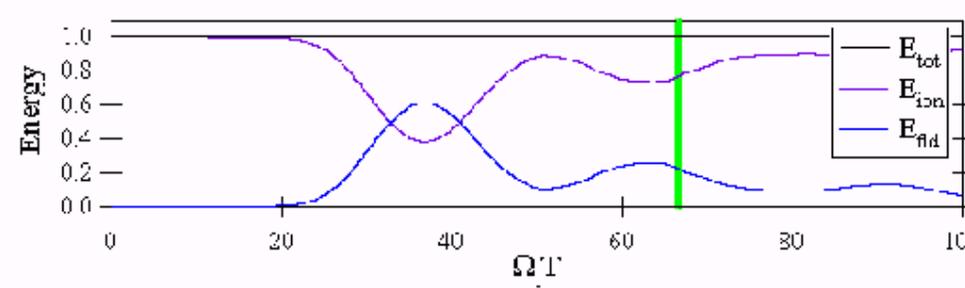
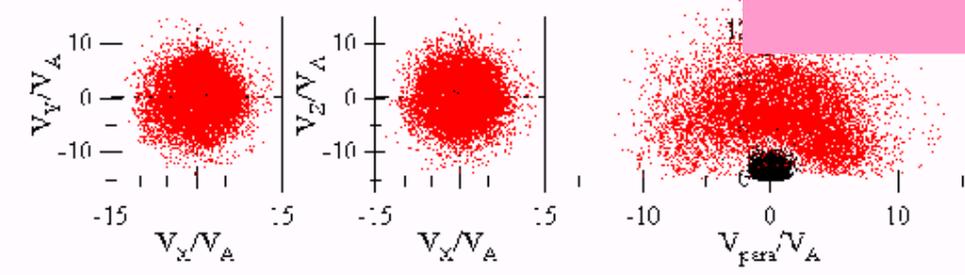
$$\omega - kV_b = -\Omega_{ci}$$

を満たすアルフェン波が励起され
 その波によりbeam ionsはピッチ角
 散乱される
 →散乱後、プラズマ系で等方化

field



MHD乱流強度のmeasure:
 $\eta = (\delta B/B_0)^{-2} \sim 5-10$.
 (太陽圏内での衝撃波 $M < \sim 10-20$)
 強い衝撃波 $M > \sim 100$ なら $\eta \sim 1$ を期待
 (Bohm limitと称する)



イオン・サイクロトロン周波数

サイクロトロン共鳴条件
 $\omega - kV_b = -\Omega_{ci}$
 を満たすアルフェン波が励起され
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CME衝撃波と電子の加速、II型電波バースト、ドリフト加速
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標準理論の拡張1... 磁場の増幅? Lucek and Bell機構

標準理論の拡張2... 加速の反作用 Cosmic Ray Mediated Shocks

More about SEP (solar energetic particles)

Ions vs. electrons

ここでLucek and Bellの議論(磁場増幅)を考える

MNRAS 314, 65 (2000)

最初の議論.... McKenzie & Voelk (1982)

Non-linear amplification of a magnetic field driven by cosmic ray streaming

S. G. Lucek[★] and A. R. Bell[★]

$\eta \sim (B_0/\delta B)^2 \ll 1$ となる可能性?!

ABSTRACT

One-, two- and three-dimensional numerical results of the non-linear interaction between cosmic rays and a magnetic field are presented. These show that cosmic ray streaming drives large-amplitude Alfvénic waves. The cosmic ray streaming energy is very efficiently transferred to the perturbed magnetic field of the Alfvén waves, and the non-linear time-scale of the growth of the waves is found to be very rapid, of the order of the gyro-period of the cosmic ray. Thus, a magnetic field of interstellar values, assumed in models of supernova remnant blast wave acceleration, would not be appropriate in the region of the shock. The increased magnetic field reduces the cosmic ray acceleration time and so increases the maximum cosmic ray energy, which may provide a simple and elegant resolution to the highest energy Galactic cosmic ray problem, where the cosmic rays themselves provide the fields necessary for their acceleration.

Key words: acceleration of particles – magnetic fields – waves – cosmic rays.

他に、Bell and Lucek, MNRAS 321, 433 (2001): 上の論文のつづき

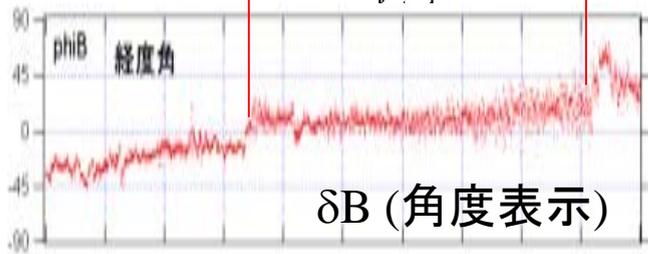
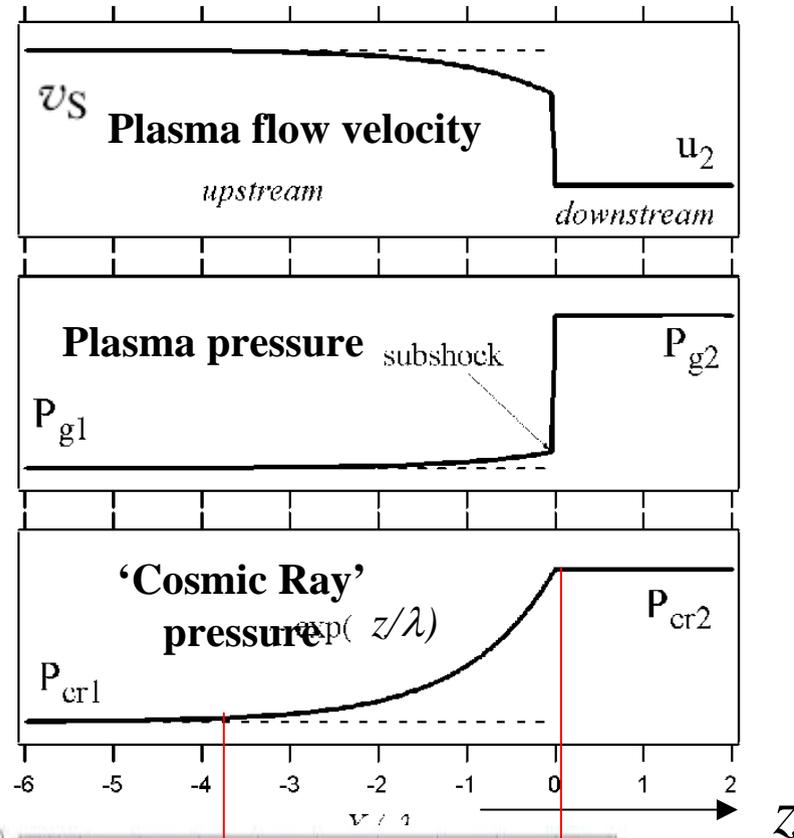
Drury et al., AA in press, aph/0309820: 応用(beyond knee?)

Lucek and Bellの議論: 磁場増幅

$$v_S \frac{\partial U_A}{\partial z} = [\text{波のエネルギー源}]$$

↑
CR粒子がする仕事

CR粒子はプラズマに対し相対速度
 $\sim -v_A$ で上流(-z方向、*i.e.* 圧力勾配方向)
 に向かって流れ出る。従ってプラズマに対し、
 $(-v_A)(-\partial P_{CR}/\partial z) = v_A \partial P_{CR}/\partial z$
 だけの仕事をする。



P_{CR} 増大とともに波のエネルギー U_A も増大

$$v_S \frac{\partial U_A}{\partial z} = v_A \frac{\partial P_{CR}}{\partial z}$$

従って、

$$U_A = \frac{v_A}{v_S} P_{CR}$$

$$U_A = \delta B^2 / 2\mu_0, v_A = B / \sqrt{\mu_0 \rho} \text{ より}$$

$$\eta^1 = \frac{\delta B^2}{B^2} = 2 \left(\frac{v_S}{v_A} \frac{P_{CR}}{\rho v_S^2} \right) \gg 1!$$

アルフェンマッハ数 ($> \sim 100$)

$O(1)$ の量

本当にこの議論が証明されたのか?



準線形理論による $(\delta B/B)^2$ の推定 (Winske and Leroy, 1985):

$$(\delta B/B)^2 \sim (n_{\text{beam}}/n_0)(V_{\text{beam}}/V_A)^2$$

と区別できていない。

というより、準線形理論の前提

$(\delta B/B)^2 < 1$ を越えた範囲(~ 10)まで、その結論、

$$(\delta B/B)^2 \sim (n_{\text{beam}}/n_0)(V_{\text{beam}}/V_A)^2$$

が使えることを示した、というべき。
(シミュレーションは衝撃波の形成をきちんと取り入れた訳ではない...
 $\partial P_{\text{CR}}/\partial z$ は入っていない!)

$$v_S \frac{\partial U_A}{\partial z} = [\text{波のエネルギー源}]$$



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CR粒子はプラズマに対し相対速度 $\sim -v_A$ で上流(-z方向、*i.e.* 圧力勾配方向) に向かって流れ出る。従ってプラズマに対し、
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$$v_S \frac{\partial U_A}{\partial z} = v_A \frac{\partial P_{\text{CR}}}{\partial z}$$

従って、

$$U_A = \frac{v_A}{v_S} P_{\text{CR}}$$

$$U_A = \delta B^2/2\mu_0, v_A = B/\sqrt{\mu_0\rho} \text{ より}$$

$$\eta^1 = \frac{\delta B^2}{B^2} = 2 \frac{v_S P_{\text{CR}}}{v_A \rho v_S^2} \gg 1!$$

アルフエンマッハ数 ($> \sim 100$)

$O(1)$ の量

という訳で、まだ彼らの議論は100%確かではない

Hillas' argument on the maximum attainable energy

(also by Makishima, 1999)

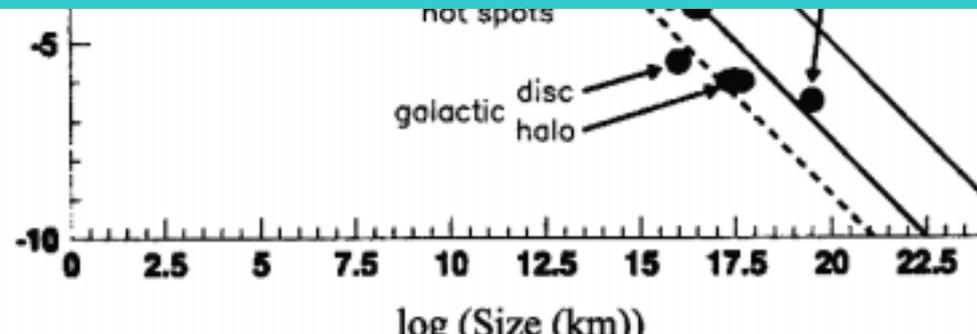
$$E_{\max} = Ze\beta B L$$

**Bを増幅することの御利益:
UHECRの起源モデルが作りやすく!**

**SNR shockによるE_{max}についての
疑問を解く**

**(Lagage & Cesarsky 1983以来の問題:
標準理論ではkneeまで1桁足りない?)**

**馬場さんのSNR解析による磁場強度
(平均的磁場の数倍以上)の説明**



the maximum
energy attainable through
acceleration process
charge number
plasma velocity (u/c)
magnetic field strength
system size

acceleration
in the Bohm limit

g condition:
($\rho_g \leq L$)

**Bを増幅してE_{max}を高める
可能性**

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(Ions vs. electrons ... 略)

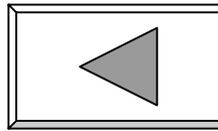
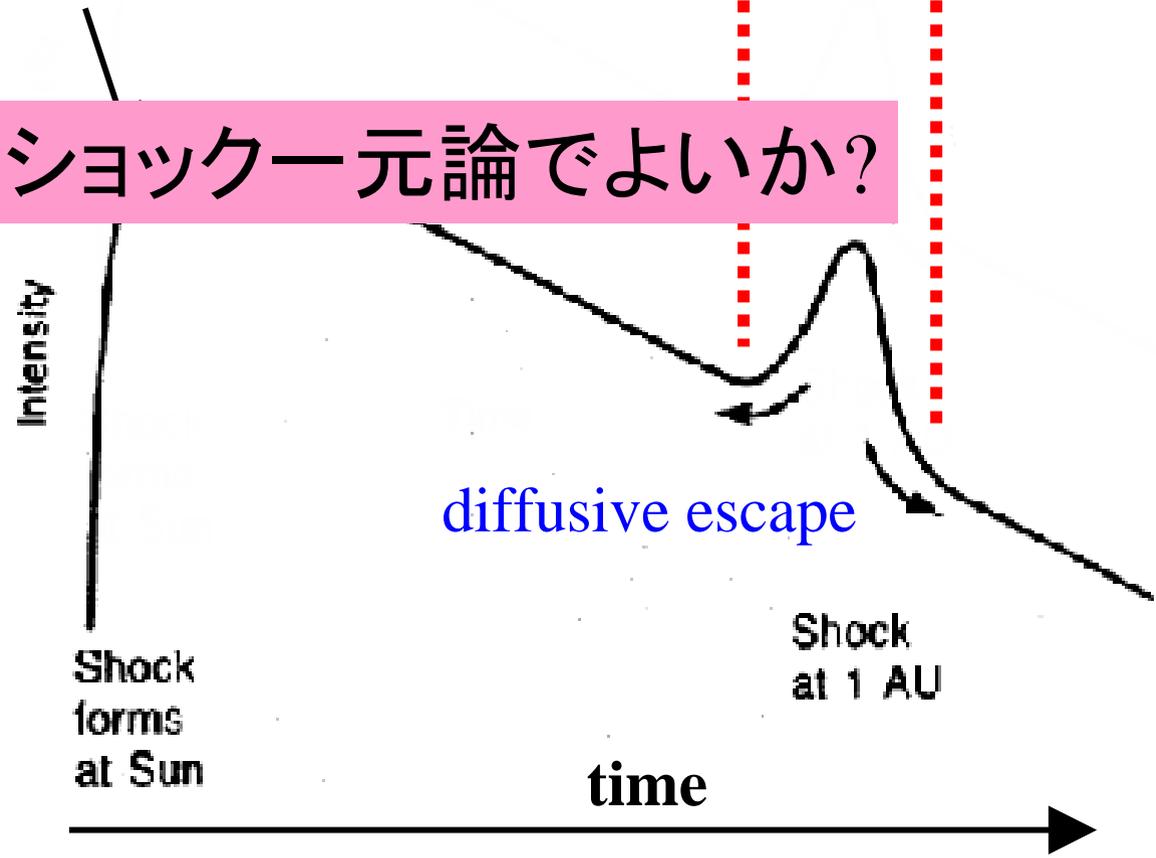
effect of local trapping

enhanced MHD turbulence

**local acceleration
by the IPS at 1AU**

product of prompt acceleration
when the IPS was near the sun

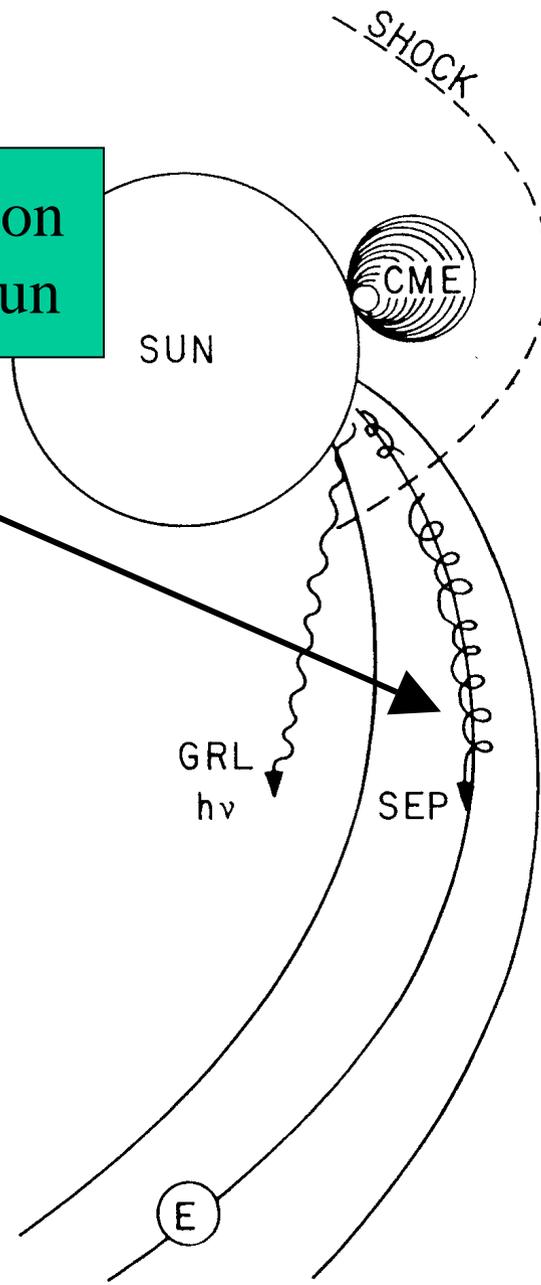
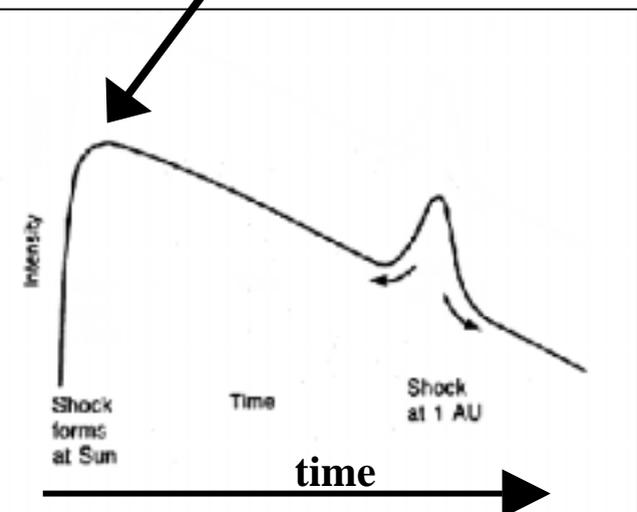
本当にショック一元論でよいか？

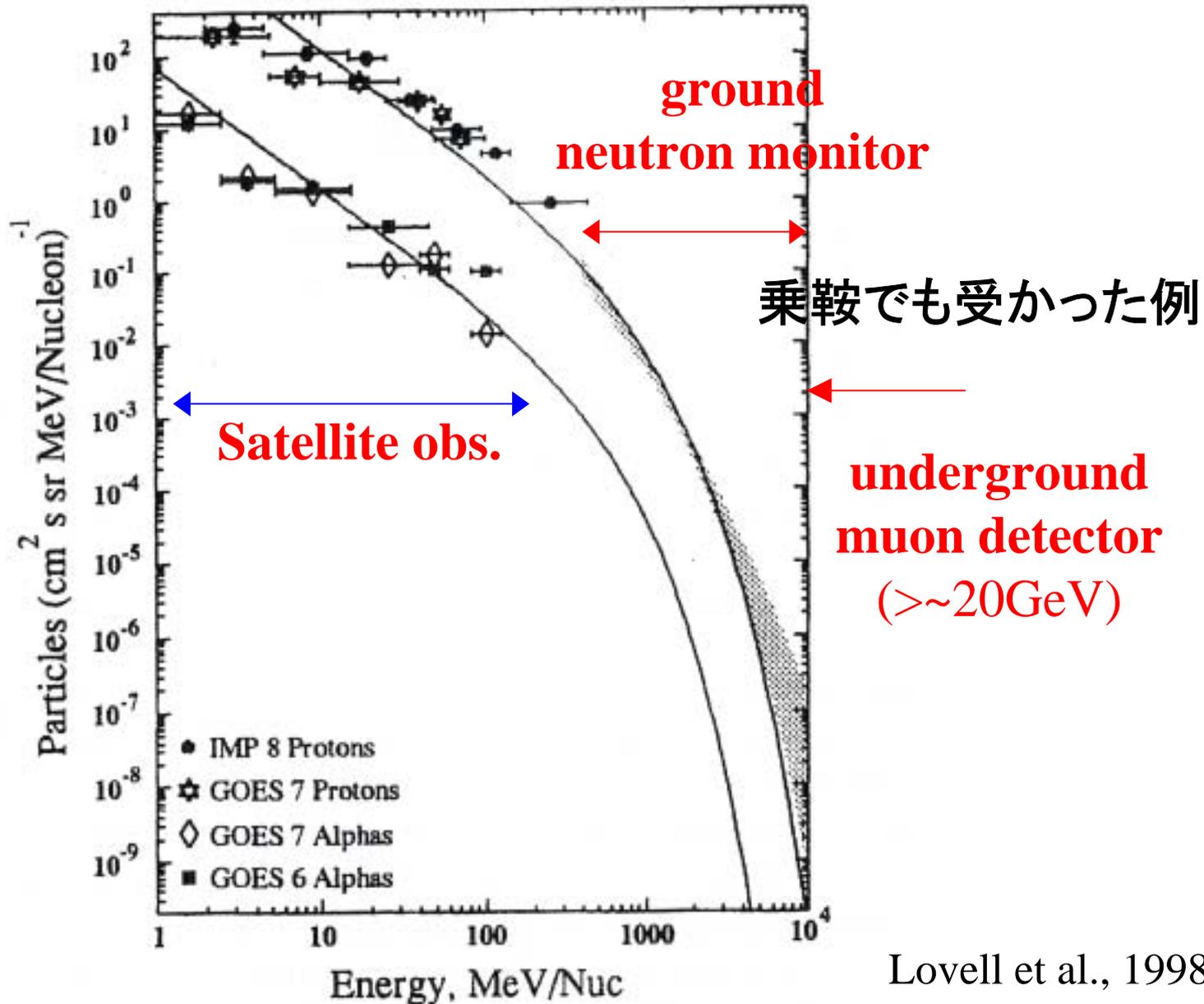


CME and SEP

L. I. MIROSHNICHENKO ET AL.

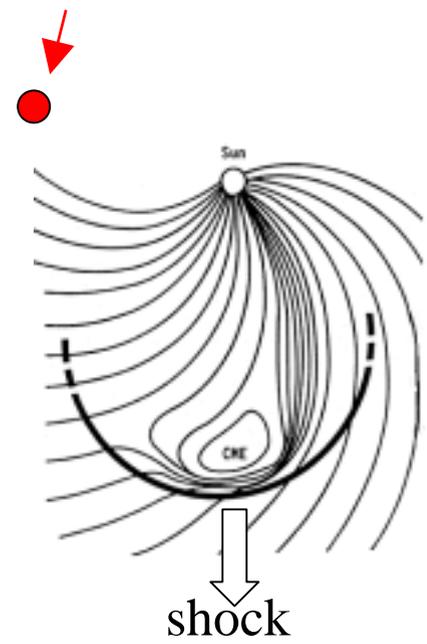
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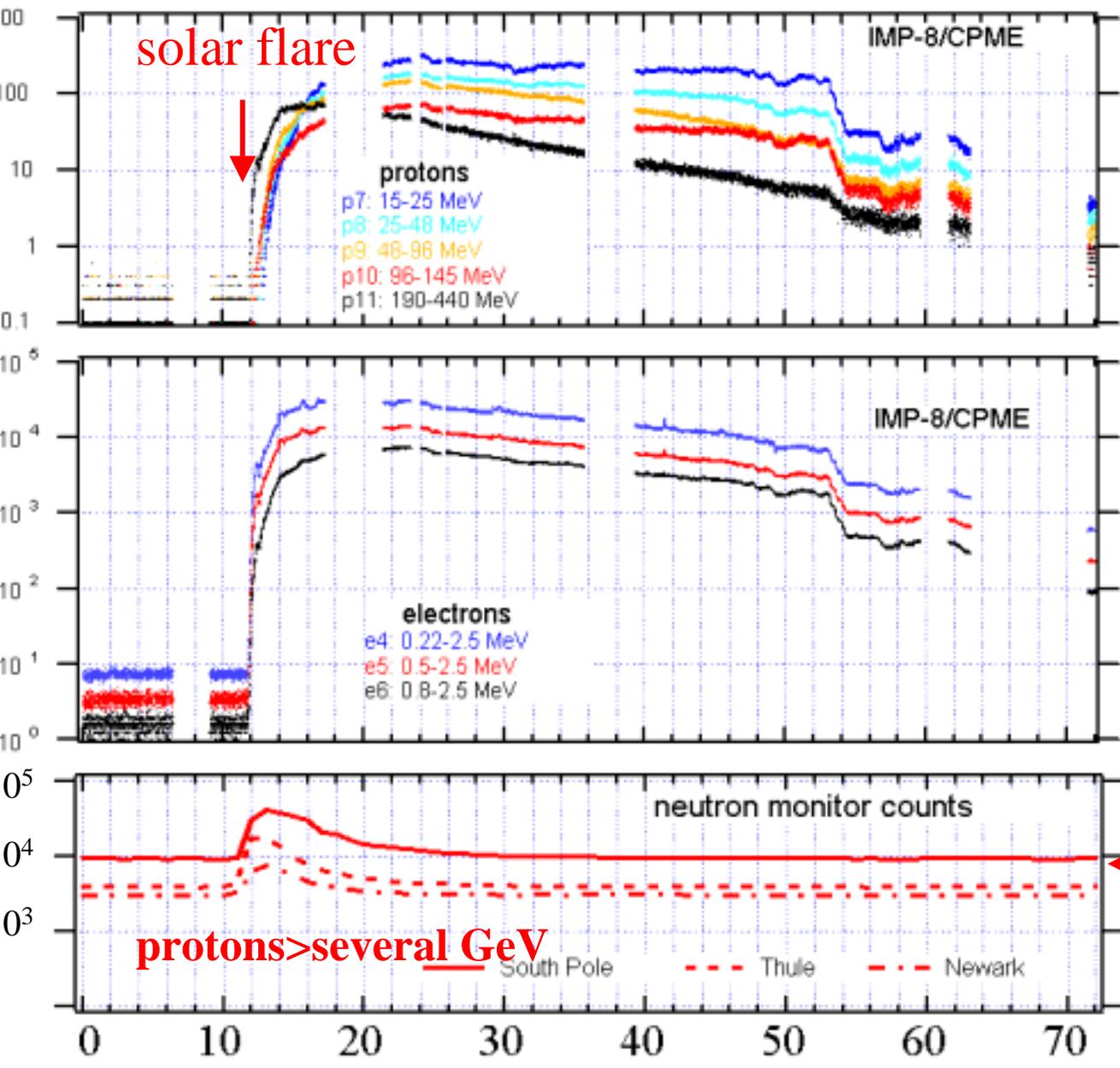


IMP-8 and Deep River neutron monitor 1989/09/29

Observer

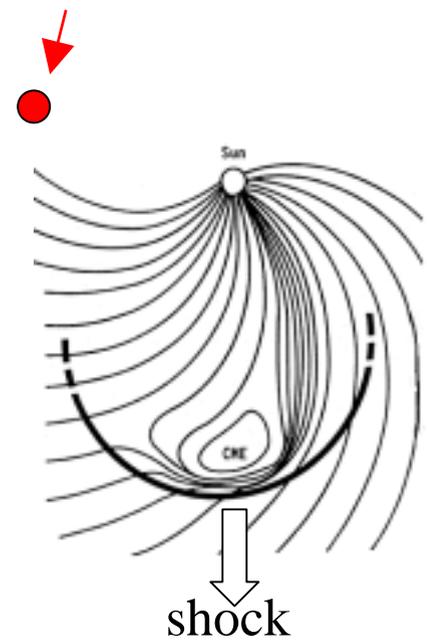


(The related solar flare occurred behind the solar limb. The CME shock did not come to the earth.)

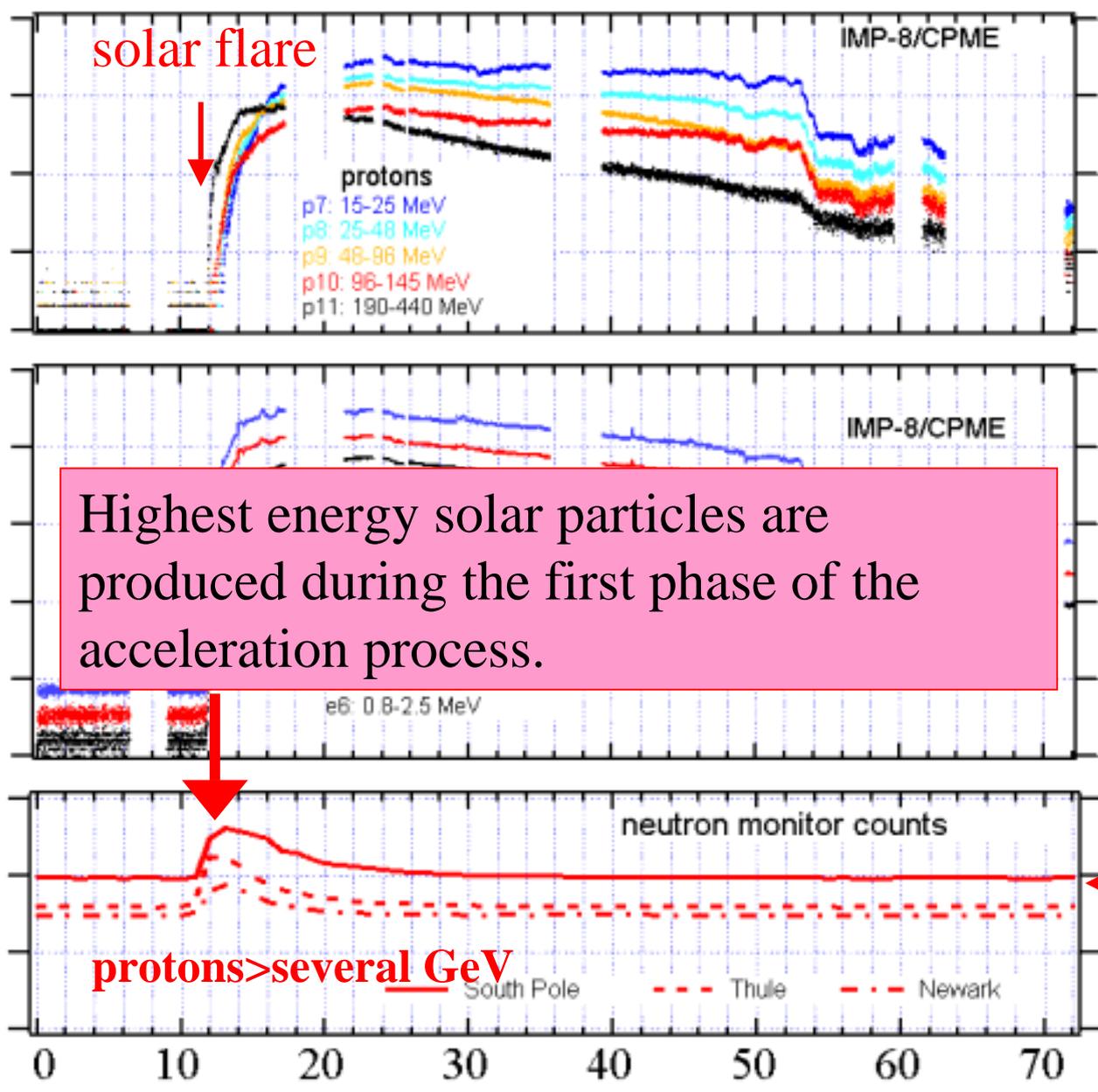


GCR level

Observer



(The related solar flare occurred behind the solar limb. The CME shock did not come to the earth.)



Highest energy solar particles are produced during the first phase of the acceleration process.

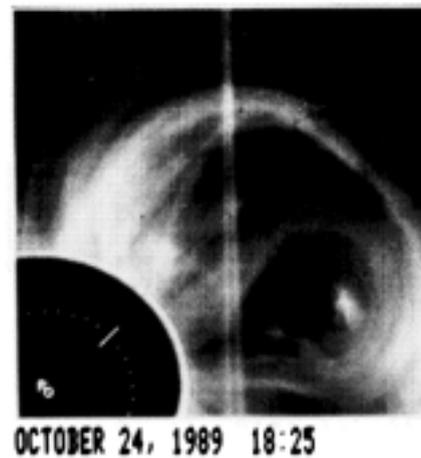
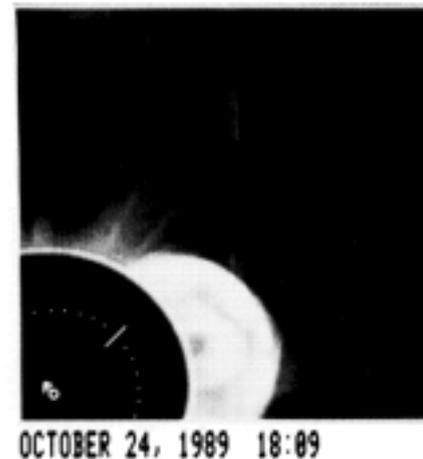
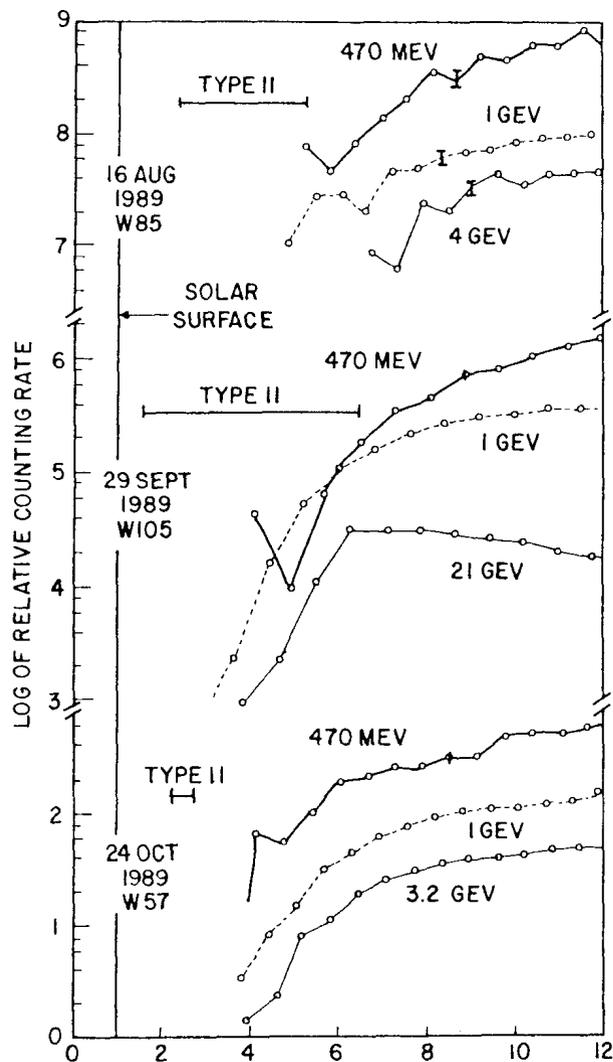
○コロナにおける加速の場所はどこか？

Kahler (1994)

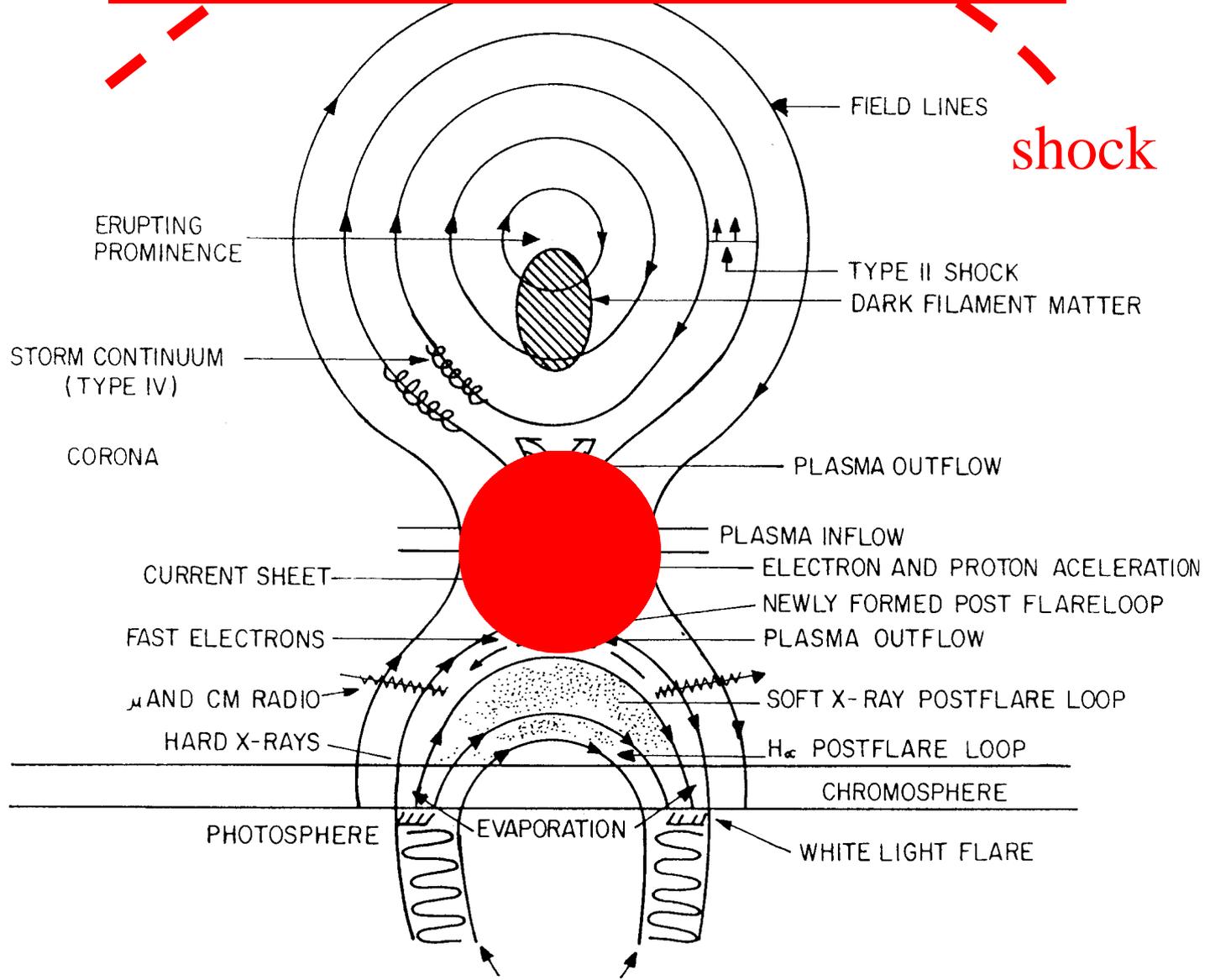
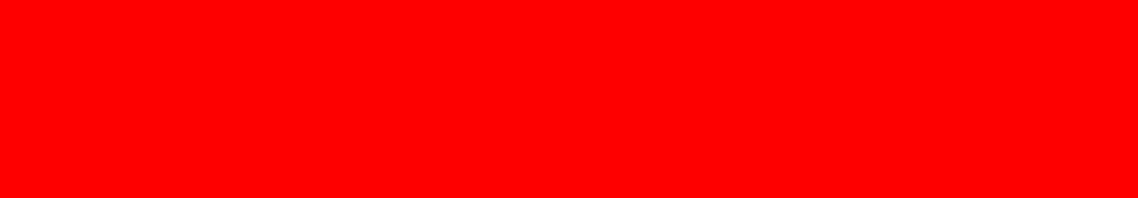
THE ASTROPHYSICAL JOURNAL, 428:837-842, 1994 June 20

INJECTION PROFILES OF SOLAR ENERGETIC PARTICLES AS FUNCTIONS OF CORONAL MASS EJECTION HEIGHTS

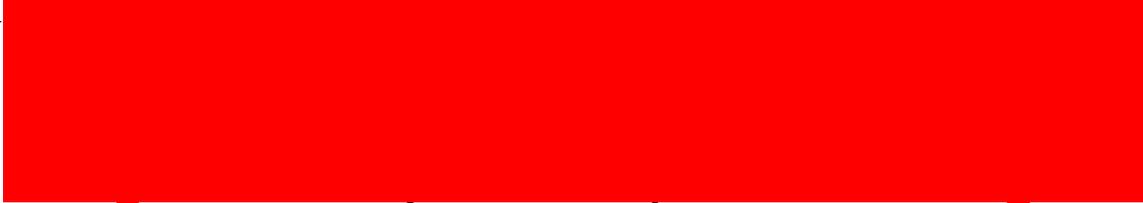
S. KAHLER



Wartens and



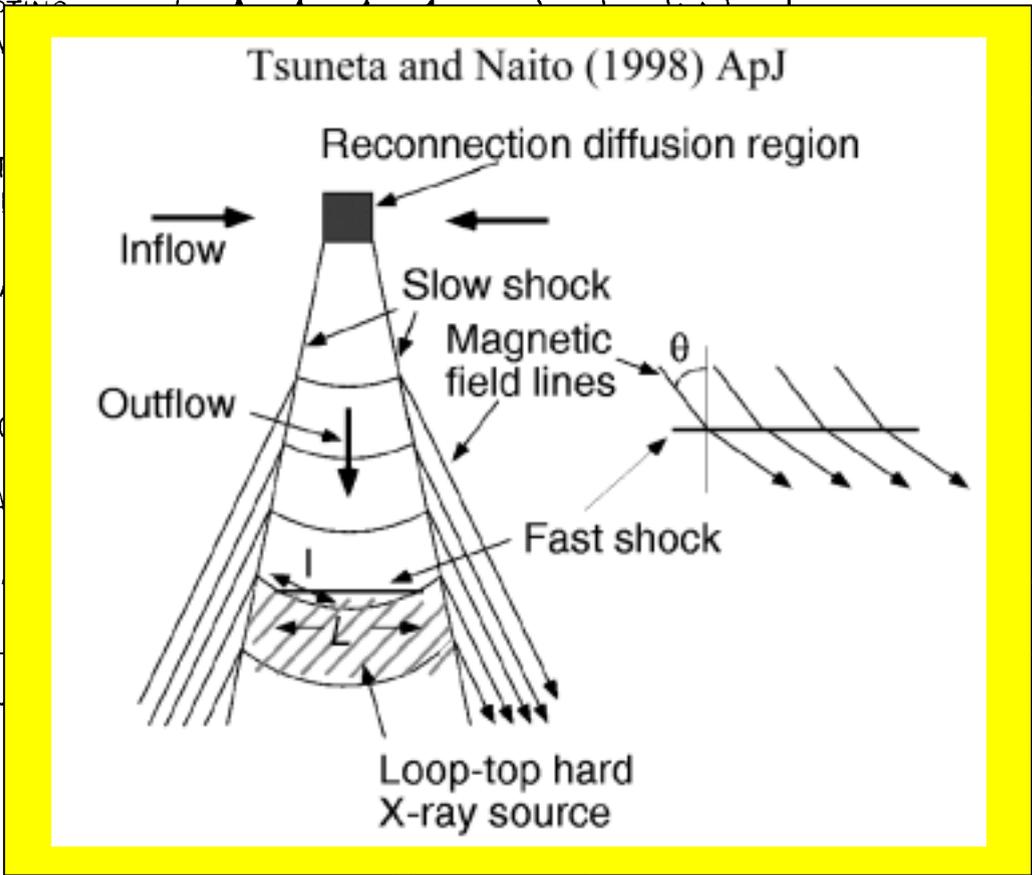
Wartens and



shock

ERUPTING PROMINENCE
STORM CONTINUATION (TYPE)
CORONAL MASS EJECTION
FASTER
MAGNETIC

IONOSPHERIC DISTURBANCE
IONOSPHERIC ACCELERATION
FLARE LOOP
FLARE LOOP
P
RE



Hillas' argument on the maximum attainable energy

(also by Makishima, 1999)

$$E_{\text{max}} = Ze\beta B L$$

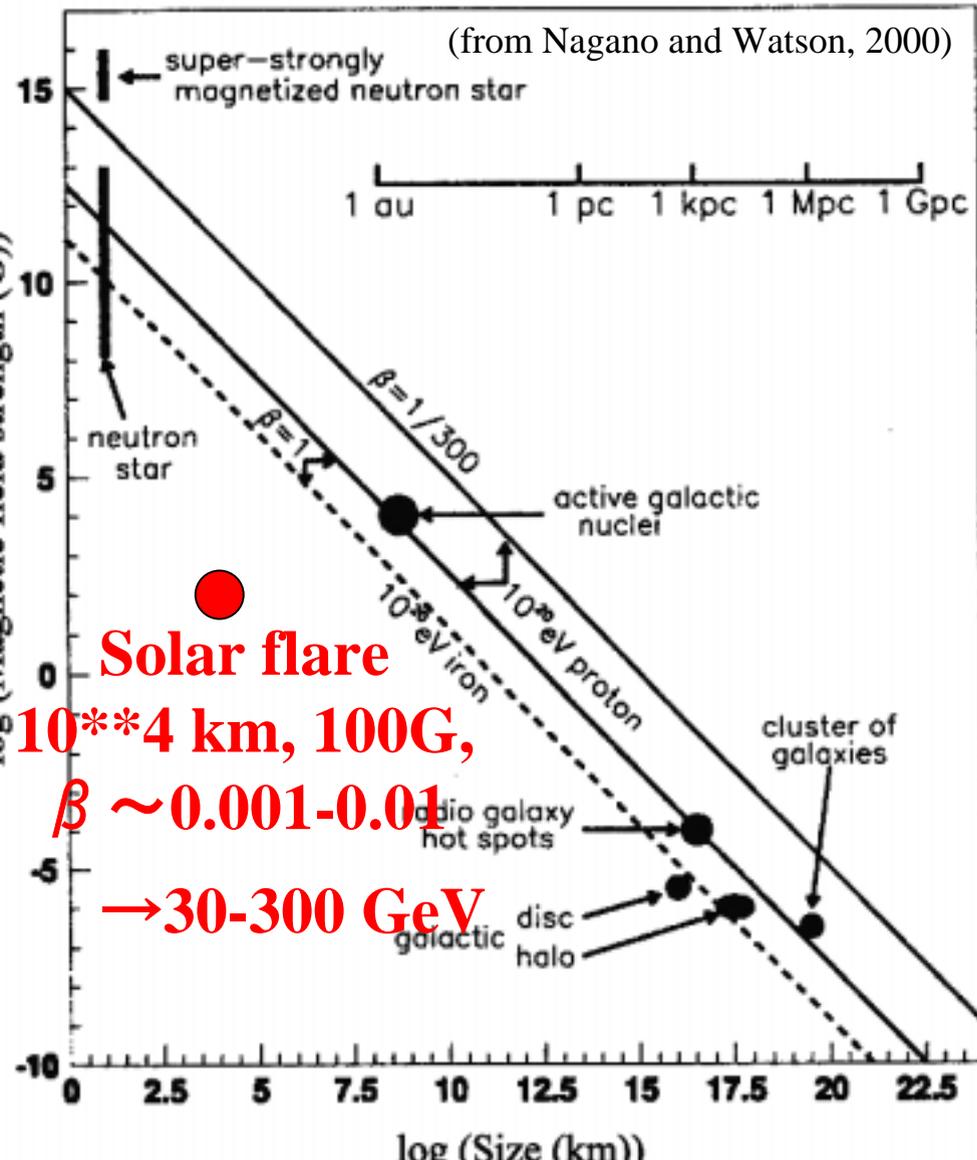
E_{max} : the maximum energy attainable through the acceleration process

Z : Charge number

β : plasma velocity (u/c)

B : magnetic field strength

L : system size



- Shock acceleration
- Trapping condition:
($\rho_g \leq L$)
- Reconnection

The end